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A QUANTITATIVE APPROACH TO DETERMINE ANALOGOUS AREAS USING ENVIRONMENTAL PARAMETERS

by

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March 2008

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The backbone of the success of the United States Naval Forces has been its ability to train for future events. By conducting successful training operations, the Navy has prepared for real-world operations. The principle, "fight like you train, train like you fight," has no less significance today than it did in the past. The purpose of this thesis is to develop a new, robust analogous area determination tool for the USN Fleet. This thesis builds upon previous approaches by expanding the potential analogous areas to the entire globe, and including more environmental parameters in the analogous area determination process. In addition, a different approach is used in determining the analogous areas. Instead of a MATLAB-based fuzzy logic approach, this method uses ArcMap software as a tool for performing analogous area searches and display of results. This method is more efficient and user-friendly than the fuzzy logic approach, and allows users to easily tailor the process to meet any requirement. The focus of this thesis is primarily on acoustic features within the water column, but other important environmental features are analyzed. The end result is an effective and accurate analogous area tool ready for immediate use in the fleet.

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A QUANTITATIVE APPROACH TO DETERMINE ANALOGOUS AREAS USING ENVIRONMENTAL PARAMETERS

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ABSTRACT

The backbone of the success of the United States Naval Forces has been its ability to train for future events. By conducting successful training operations, the Navy has prepared for real-world operations. The principle, “fight like you train, train like you fight,” has no less significance today than it did in the past. The purpose of this thesis is to develop a new, robust analogous area determination tool for the USN Fleet. This thesis builds upon previous approaches by expanding the potential analogous areas to the entire globe, and including more environmental parameters in the analogous area determination process. In addition, a different approach is used in determining the analogous areas. Instead of a MATLAB-based, fuzzy logic approach, this method uses ArcMap software as a tool for performing analogous area searches and display of results. This method is more efficient and user-friendly than the fuzzy logic approach, and allows users to easily tailor the process to meet any requirement. The focus of this thesis is primarily on acoustic features within the water column, but other important environmental features are analyzed. The end result is an effective and accurate analogous area tool ready for immediate use in the fleet.

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LIST OF ACRONYMS AND ABBREVIATIONS

ArcGIS	A suite of ESRI Geographic Information Systems software
ArcMap	The primary component of ArcGIS used in mapping, editing, querying, and display geospatial data
ASCII	American Standard Code for Information Interchange
ASW	Anti-submarine Warfare
CASS/GRAB	Comprehensive Acoustic Simulation/Gaussian Ray Bundle; an active sonar propagation loss model
°C	degrees Celsius
COADS	Comprehensive Ocean-Atmosphere Data Set
CONUS	Continental United States
CTD	Conductivity/Temperature/Depth probe
CZ	Convergence Zone
DI	Directivity Index
.dbf	database file
DOD	Department of Defense
DSC	Deep Sound Channel
DSCA	Deep Sound Channel Axis
DSCD	Deep Sound Channel Depth
DT	Detection Threshold
ESA	Environmental Site Analyzer
ESRI	Environmental Systems Research Institute; a GIS and mapping software company
ft	feet

FORTRAN	A programming language
Gamma	The rate of change of sound speed with depth; referenced to the thermocline
GDEM-V	Generalized Digital Environmental Model Variable Resolution
GIS	Geographic Information Systems
GTS	Global Telecommunication System
HFEVA	High Frequency Environmental Acoustics
HITS	Historical Temporal Shipping
Hz	hertz
ILD	Isothermal Layer Depth
kHz	kilohertz
km	kilometers
m	meter
m/s	meters per second
MATLAB	The MATLAB scientific programming language
METOC	Navy Meteorology and Oceanography community
MIW	Mine Warfare
MLD	Mixed Layer Depth
MLT	Mixed Layer Temperature
MOODS	Master Oceanographic Observation Data Set
NaN	MATLAB-recognized “not a number”
NAVOCEANO	Naval Oceanographic Office
NCDC	National Climatic Data Center

NetCDF	Network Common Data Format
NGDC	National Geophysical Data Center
NIMA	National Imagery and Mapping Agency (NIMA)
NL	Noise Level
nm	nautical mile
NMLD	Naval Research Laboratory Mixed Layer Depth
NOAA	National Oceanic and Atmospheric Administration
RL	Reverberation Level
.shp	ESRI shapefile
SL	Source Level
SMGC	Surface Marine Gridded Climatology
SNR	Signal to Noise Ratio
SOFAR	Sound Fixing and Ranging
SS	Sound Speed
SSP	Sound Speed Profile
SST	Sea Surface Temperature
SVP	Sound Velocity Profile
TL	Transmission Loss
TS	Target Strength
.txt	text file
US	United States
USN	United States Navy

USW	Undersea Warfare
XBT	Expendable Bathythermograph

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The author would like to thank Assistant Professor D. Benjamin Reeder, CDR, USN, for highlighting the subject of analogous areas and allowing him to develop the subject into a thesis. His efforts in providing guidance, reference material, and datasets are much appreciated and his efficiency in responding to the author's requests from the eastern coast of the United States aided in completing this thesis. The author would also like to thank Professor Mary L. Batteen for the time and effort she gave up to discuss the options and direction within the thesis. Words of encouragement from both CDR Reeder and Professor Batteen inspired the author through the entire process.

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I. BACKGROUND

A. BACKGROUND

In order for the United States Navy (USN) to maintain its superiority of the seas it is imperative that it continue to follow the same principle that has been followed for years. That is, to train like you fight and fight like you train. The ability to understand and tactically use the ocean environment is critical for successful USN exercises and operations. The challenge is finding areas as close as possible to homeports that will present a similar environment to the one in which the "fighting" will take place. Consider an Anti-submarine Warfare (ASW) operation with surface ships searching for an enemy submarine. When engaged in submerged operations, without visual aids and radar, submarine sonar operators must listen to the ocean environment in order for the submarine to remain undetected and out of harms' way. Similarly, surface ships must use their sonar to try to detect the submarine. The physics of ocean acoustic propagation, which is determined by the ocean environment, determine whether or not it will be heard or detected.

In recent years, ASW has garnered much interest from USN officials. Collaboration between the Submarine force and the Naval Warfare Development Center has identified the need for a tool to aid in the determination of analogous areas so that USN forces can effectively train in environmentally similar areas to those where operations will be conducted. This requires significant evaluation of the parameters that affect sound propagation and how they change temporally and spatially. Bathymetry, bottom type, sediment thickness, and ambient noise are all parameters affecting submarine detection and need evaluation. Perhaps the most important of these is the sound speed profile (SSP), also known as the sound velocity profile (SVP). If a set of parameters could be defined to characterize the SSP, selection criteria could be produced to find ocean areas similar to areas of expected operations. These selection criteria would vary depending on mission type. Several attempts to characterize the SSP and determine a method to locate analogous areas have been attempted, with two of the more recent ones discussed here. Shortcomings are evident in these earlier approaches, making clear the need to develop a more thorough and useful tool in analogous area determination that is of more immediate use to the fleet.

1. Miyamoto and Kooiman's Environmental Site Analyzer (ESA)

Mr. Bob Miyamoto and Mr. Bill Kooiman of the Applied Physics Laboratory (APL) at the University of Washington developed the Environmental Site Analyzer (ESA) in the late 1990's (Miyamoto, 1999). The motivation behind the ESA was the need to design acoustic systems to operate effectively in a variety of locations. While conducting developmental testing in the continental United States (CONUS) waters reduces costs and resources, evaluating system performance in areas analogous to waters in other parts of the world would maximize the value of the testing. Areas were selected to meet the following criteria: 28 locations (14 in CONUS waters and 14 overseas), sized 60 nautical miles (nm) by 60nm, and only shallow water (<500 meters (m)) data within the 1200 square nautical mile area used in determining analogous areas. The ESA is very useful for the specific purpose of finding locations to test acoustic systems in CONUS; however, the ESA is not as useful for applications specific to USN training and operations (operating outside CONUS).

The Miyamoto ESA uses sound speed profiles (grouped into one of nine categories), bathymetry, bottom characteristics, rainfall data, shipping density, and wind speed as parameters of interest to determine analogous areas. Table 1 gives the nine SSP categories used in the ESA.

ISOVELOCITY	Max – Min< 2 m/s
UPWARD REFRACTING	Min at surface and Max at bottom
CHANNEL	Min not at surface or bottom
DEEP LAYER	Max > 200 ft
INTERMEDIATE LAYER	75 ft < Max < 200 ft
SHALLOW LAYER	25 ft < Max < 75 ft
MILDLY DOWNWARD REFRACTING	Max < 25 ft and slope (below layer gradient) < 0.05
INTERMEDIATE DOWNWARD REFRACTING	Max < 25 ft and 0.05 < slope < 0.1
STEEP DOWNWARD REFRACTING	Max < 25 ft and slope > 0.1

Table 1. Environmental Site Analyzer (ESA) SSP Types. Max and Min refer to the maximum and minimum sound speeds in the profile. [From Miyamoto, 1999].

At the heart of the ESA is a comparison algorithm that determines the similarity of two sites based on the environmental parameters. This algorithm is implemented using fuzzy logic to handle the three different types of parameters (binary/multi-level, numerical, statistical) used. Each parameter is assigned membership into one or more fuzzy sets, after which, fuzzy entropy is used to measure the similarity of the parameters at two different sites. Once accomplished, heuristic rules are applied to the parameters to control their weight. Binary and multi-level parameters, such as bottom loss, are assigned membership into one of three sets (low, medium, and high), based on classical set theory. If, for example, bottom loss at a particular site was evaluated as low, then its assigned membership into the fuzzy low set is 1.0 and zero in the fuzzy medium and fuzzy high sets. Numerical parameters, such as shipping, are assigned into one or more of the three fuzzy sets based on the rank of the site compared to all other sites. The fuzzy sets of low, medium, and high correspond to the 0th percentile, 50th percentile, and 100th percentile, respectively. For example, a value of 0.6 (60th percentile) would be assigned a zero membership into the fuzzy low set, but have a 0.8 membership in the fuzzy medium set and a 0.2 membership in the fuzzy high set. Finally, statistical parameters like sound speed are assigned membership into the fuzzy sets based on the percentage of observations of each type of the nine SSP classifications. The likeness between two sites is then determined. The likeness, or fuzzy entropy, is determined from the ratio of the sum of the minimum of the fuzzy set memberships to the sum of the maximum of the fuzzy set memberships. Weights are then assigned based on heuristic rules. Suppose that the SSP for a particular site was determined to be upward refracting where all sound waves leaving any point in the profile refract towards the surface. In such an example, bottom parameters would be less important and assigned a lower weight than other parameters. The final step of the ESA multiplies the likeness factor of each parameter by its weight, adds them up, and then divides the total by the sum of the weights to achieve the similarity match score of the two sites. Because the data used in the ESA is only for shallow water, this approach is not effective outside shallow water areas and would require a different set of heuristic rules to determine weights for areas where deeper waters exists. This is the approach taken by LCDR Keith Everett and is discussed next.

2. LCDR Keith Everett's USW Area Analogs

For his master's thesis entitled "USW Area Analogs," LCDR Keith Everett, USN, developed a method to determine undersea warfare analogous areas within the USN Fleet Training Areas. LCDR Everett attempted to further build upon the idea and methodology of Miyamoto's ESA by constructing an approach taking deep water areas into account.

The first step in the process was to define methodology to characterize the SSP. Several methods, ideally, can be used to define the SSP. One approach would be to take only several key parameters, like Mixed Layer Depth (MLD) or Deep Sound Channel Axis Depth (DSCD) and compare them between locations. Another option would be to compare the profiles point by point and assign matches based on how many points the profiles have in common. Categorizing the SSPs, as in the ESA, is also another alternative (Everett, 2005, p.23-24). The SSP can be very complex, especially in deeper waters, so none of the methods above are robust enough to perform an accurate classification. A more accurate method, used by LCDR Everett, is to generate a larger, more descriptive, set of parameters corresponding to key features in the profile. These parameters then become the fuzzy logic sets used to identify analogous areas. Many of these parameters were used for the SSP characterization in this thesis and will be discussed in Chapter II.

After identifying the SSP's key parameters, LCDR Everett extracted sound speed data from the Generalized Digital Environmental Model (GDEM) database and imported it into MATLAB scientific language code, where a program classified the ingested sound speed data. The output of the program was a set of matrices containing 19 descriptive parameters for each selected latitude and longitude location. One matrix contained the parameter values for the USN Fleet Training Areas (East Coast, West Coast, and Hawaii) and a second matrix for a selected target area. A second and third program was then utilized to add sediment thickness values to the previous USN and target area matrices, respectively. The output was a matrix containing 20 descriptive parameters for each SSP: three for location and month, four binaries used for heuristic rules, and 13 for physically describing the SSPs (Everett, 2005, p.50).

The next step in the process formed the fuzzy entropy sets, based on ranking the 13 physical parameters by percentile within the entire data set. As in the ESA, three fuzzy set membership groups were used (high, medium, and low) corresponding to the 100^{th}, 50^{th}, and 0^{th} percentile, respectively. The fuzzy entropy was calculated, as discussed previously, creating a fuzzy entropy matrix. The four binary parameters were then used in heuristic rules to determine the weights applied to the 13 physical parameters. A "weight" matrix was generated and multiplied by the fuzzy entropy matrix to produce a set of weighted entropies for each location. After summing the weighted entropies and normalizing by the sum of the weights for each location, the output consisted of a set of total weighted fuzzy entropies by location and month, representing the "match score" for each location compared to the target location (Everett, 2005, p. 53, 55-56). These steps were also completed using an additional MATLAB program. In order to provide a display of the match score, ArcMap software was used. An example of a monthly match score display for a deep water example is shown in Figure 1. A more in-depth discussion of ArcMap will be included in Chapter III, as the software is used extensively in this thesis.

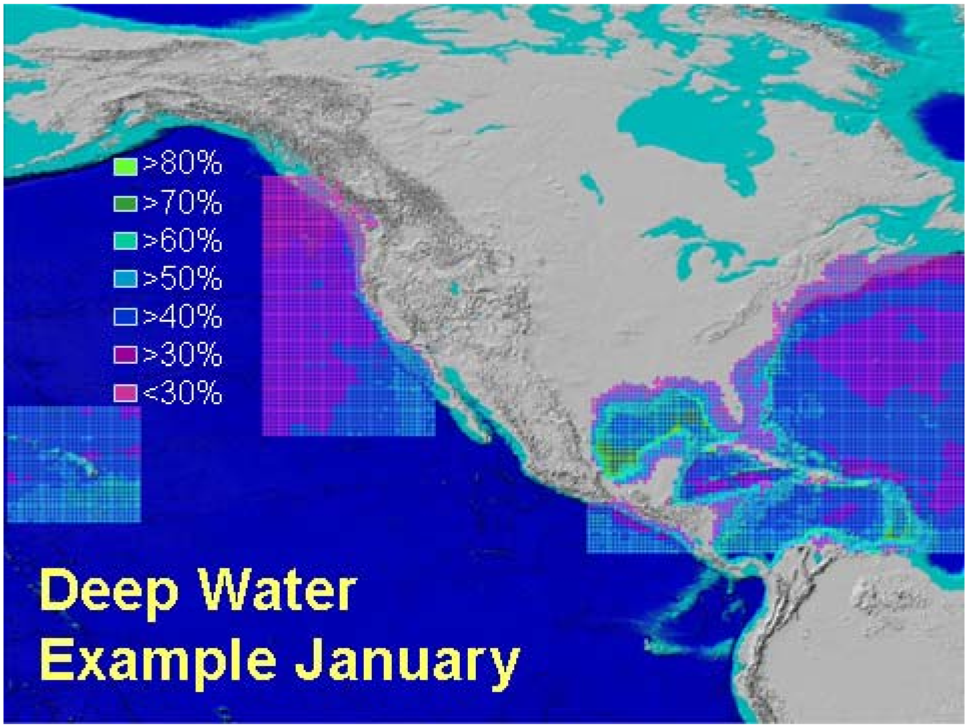

Figure 1. Match Score for January in Deep Water. [From Everett, 2005, p. 92].

Both Mr. Miyamoto's ESA and LCDR Everett's USW Area Analogs failed to take full advantage of the range of data and resources available for determining analogous areas. While their work was quite beneficial in providing the ground work for analogous area determination, the process used in this thesis generates the necessary criteria for accurately determining analogous areas. The methodology and data used covers the global oceans and seas and allows for determining analogous areas for any location USN surface ships and submarines may operate. Additionally, the method used in this thesis is useful for various USN organizations and can be tailored to meet any mission that requires at-sea training. As additional databases become available, the ArcMap software used in this thesis for both analogous area determination and display allows for the easy importation of such data so more search criteria can be used.

B. OUTLINE

The organization of this thesis is discussed below. Chapter II presents the methodology and description of the parameters used to characterize the sound speed profile (SSP), as well as describing ocean bottom parameters and ocean surface factors (wind and wave height) beneficial to analogous area determination. Also included are the databases from which the acoustically important data can be obtained. Chapter III presents the process used to acquire and manipulate the data for importation into ArcMap software. Chapter IV presents the in-depth process and methodology that an analogous area determination tool user would perform to determine analogous areas. Chapter V presents the results of testing and validating the tool with an example scenario. Finally, conclusion and recommendations are presented in Chapter VI. Because a crucial aspect in finding analogous areas is data processing and manipulation, a flowchart and subsequent description will be included to guide the reader through the actual process used in this thesis.

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II. APPLICABILITY OF ENVIRONMENTAL AND OCEANOGRAPHIC PARAMETERS

A. DATA REQUIREMENT

Determining the acoustically significant data useful in an analogous area tool is critical to ensuring that results are accurate and trustworthy. Selection of this data requires analysis of the processes underlying the detectability of an underwater submarine or mine and is characterized by the passive and active sonar equations. Proper utilization of data that represent inputs into the sonar equations allows for prediction of sound propagation and, therefore, analogous area determination. Since the primary focus of a submerged submarine is to remain undetected, minimizing the acoustic transmission is extremely important. For surface ships and submarines engaging in ASW operations, both active and passive sonars will be utilized to either remain undetected (submarine) or to detect. Success or failure of this is quantified by the active and passive sonar equations below (Urick, 1983, p. 29):

Active Sonar Equations:

Noise background

$$SL - 2TL + TS = NL - DI + DT$$

Reverberation background

$$SL - 2TL + TS = RL + DT_R$$

Passive Sonar Equation:

$$SL - TL = NL - DI + DT_N$$

where

SL = Source Level. In the active sonar equation, the amount of sound emitted by a sound source is the SL (Urick, 1983, p. 71). For the passive case, SL is defined as the intensity of the noise that is radiated to a distance by an underwater sound source (Urick, 1983, p. 328-329). For both cases, SL is normally defined at a distance of 1 meter (m) from the source.

TL = Transmission Loss. Quantitatively, TL expresses the weakening of sound between a point 1 m from the sound source and a point at some distance in the ocean. TL is a representation of the delay, distortion, and weakening of sound as it propagates through the ocean medium (Urick, 1983, p. 99). In the active sonar equation TL is doubled to account for the 2-way sound travel from source to target and back to the source.

TS = Target Strength. TS describes the echo returned by an underwater target and is defined as the ratio of intensity of the sound returned by a target to the radiated intensity from a distant source (Urick, 1983, p. 291).

DI = Directivity Index. DI is an expression for array gain in terms of the directional functions of the signal and noise (Urick, 1983, p. 42).

DT = Detection Threshold. The ratio of the signal power to the noise power, measured at the receiver, that is required for detection at some pre-assigned level of correctness defines the DT (Urick, 1983, p. 378-379). In other words, it is the level above the background noise that is required for an operator to detect a signal.

NL = Noise Level. NL is that portion of sound that is not attributed to identifiable sources. It is made up of two components: self-noise, due to the sonar hydrophone and its mounting, and ambient noise, due to the environment (Urick, 1983, p. 202, 354).

RL = *equivalent plane-wave* Reverberation Level. RL is defined as the intensity of an axially incident plane wave producing the same hydrophone output as the observed reverberation, where reverberation is the total sum of the scattering contributions from all scatterers. There are three types of reverberation scatters in the ocean: volume scatterers such as marine life, sea-surface reverberators on or near the ocean surface, and bottom reverberators on or near the ocean bottom (Urick, 1983, p. 237-238, 240-241).

The sonar equations describe the relationship (equality) between the desired portion of an acoustic field called the signal (echo or sound from a target) and an undesired portion called the background (noise or reverberation). When a target is just being detected, the combination SL – 2TL + TS – (NL – DI), termed signal-to-noise ratio (SNR), is equal to DT (Urick, 1983, p. 21). If SNR is greater than DT, a sonar operator will determine that a target is present. Conversely, if SNR is less than DT, a target can be considered absent.

Several of the parameters in the passive and active sonar equations can be controlled by humans, while others are not. Projector and target source level (SL), self-noise level (NL), receiver directivity index (DI), and target strength (TS) are parameters that can be controlled in the manufacturing process or by operators. Transmission Loss (TL), reverberation level (RL), and ambient-noise level (NL) are parameters which can be somewhat controlled in an operational sense, but are primarily determined by the environment and require further discussion (Urick, 1983, p. 19).

Transmission Loss (TL) is the result of losses due to spreading and attenuation. Spreading losses are due to the natural weakening of sound as it spreads outward from a source. Attenuation losses include losses due to absorption, scattering, and leakage out of sound channels. Spreading and attenuation losses vary with range, depth, and frequency, and are path-dependent (Urick, 1983, p. 100, 103, 108).

Noise Level (NL), as previously mentioned, is that portion of the ocean noise that is left after all identifiable sources have been accounted for (Urick, 1983, p. 202). The ambient noise portion of NL is attributed to factors primarily out of control of the sonar operator. Shipping, biologics, waves and tides, seismic disturbances such as thermal vents and earthquakes, and rainfall all affect the background noise in the ocean and can make it difficult for operators to detect submarines operating in or near regions of these activities.

B. SOUND SPEED PROFILES (SSP)

1. Sound Speed History, Background, and Construction

In the early nineteenth century, the first measurement of sound speed was taken and it was realized that knowing the sound speed in water had significant implications in acoustical oceanography applications (Medwin and Clay, 1998, p. 4). The speed of sound in the ocean is a function of temperature, salinity, and pressure and varies with location and time of year. As a rule of thumb, temperature affects sound speed such that it increases 3.2 meters per second (m/s) per degree Celsius (°C), and salinity causes an increase of 1.4 m/s per parts per thousand (0/00). Additionally, a change in depth of 100 m will cause an approximate increase in sound speed of 1.6 m/s (NAVOCEANO, 1999, p. 3). Generally, temperature is the dominant contributor to sound speed in the upper profile of the ocean in deep waters, while salinity contributions are quite minor except near locations where there is an abundance of fresh water sources (polar regions, river runoff) (Medwin and Clay, 1998, p. 4) or near very saline waters in places like the Mediterranean and Arabian Seas.

Empirical formulas for sound speed have been determined from laboratory experiments over the past 50 years and with the advent of the computer, well-constructed, complex equations for sound speed can now be solved to many significant digits in a short amount of time. While simplified formulas for sound speed exist that provide a small error, the best expression to obtain sound speed values from temperature, salinity, and depth is the Del Grosso equation (Medwin and Clay, 1998, p. 84). The Del Grosso equation, given below, was compared to other sound speed equations after its development and it was concluded that if an accuracy of ± 0.3 m/s were adequate, simpler equations would suffice. The largest concern for the simplified equations of sound speed is that on occasions where the sound speed difference of two depths is more important than the actual sound speed at those depths, simplified equations would not be sufficient, even if accurate corrections were applied to the sound speed values (Del Grosso, 1974, p. 1090). The Del Grosso equation is used to determine sound speed in this thesis.

$$C_{STP} = C_{000} + \Delta C_T + \Delta C_S + \Delta C_P + \Delta C_{STP}$$

where

$$C_{000} = 1402.393$$

$$\Delta C_T = 0.501109398873 \times 10^{1}T - 0.550946843172 \times 10^{-1}T^2 + 0.221535969240 \times 10^{-3}T^3,$$

$$\Delta C_S = 0.132952290781 \times 10^{1}S + 0.128955756844 \times 10^{-3}S^2,$$

$$
\begin{aligned}
\Delta C_P = {} & 0.156059257041 \times 10^{0} P \\
& + 0.244998688441 \times 10^{-4} P^2 \\
& - 0.883392332513 \times 10^{-8} P^3,
\end{aligned}
$$

$$
\begin{aligned}
\Delta C_{STP} = {} & -0.127562783426 \times 10^{-1} TS \\
& + 0.635191613389 \times 10^{-2} TP \\
& + 0.265484716608 \times 10^{-7} T^2 P^2 \\
& - 0.159349479045 \times 10^{-5} TP^2 \\
& + 0.522116437235 \times 10^{-9} TP^3 \\
& - 0.438031096213 \times 10^{-6} T^3 P \\
& - 0.161674495909 \times 10^{-8} S^2 P^2 \\
& + 0.968403156410 \times 10^{-4} T^2 S \\
& + 0.485639620015 \times 10^{-5} TS^2 P \\
& - 0.340597039004 \times 10^{-3} TSP
\end{aligned}
$$

where T is temperature in degrees Celsius, S is salinity in parts per thousand (0/00), and P is pressure in kilograms per square centimeter gauge (Del Grosso, 1974).

Sound speed profiles (SSPs) provide a graphical representation of the variation of sound speed with depth. SSPs can be determined by direct measurements using Conductivity, Temperature and Depth (CTD) sensors or by using computers to determine sound speed from bathymetry (XBT) measurements, historical bathymetry and salinity measurements (Naval Oceanographic Office (NAVOCEANO), 1999, p. 2-3). A typical mid-latitude SSP is shown in Figure 2.

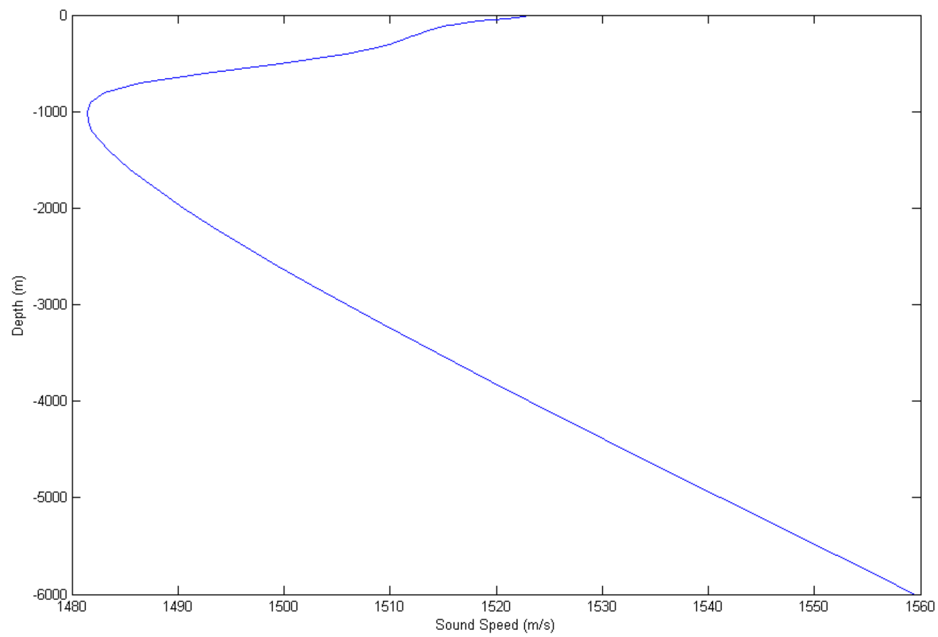

Figure 2. Typical Mid-Latitude Sound Speed Profile (SSP).

2. SSP Characterization

In the previous chapter several methods were mentioned as possible ways to characterize the SSP. Characterization requires more than just identifying a few key features because acoustic propagation cannot be adequately described by only several key parameters. A point-by-point comparison of two profiles, where the number of common points determines a match, is also an ineffective method to characterize the SSP because a small bias error between similar profiles would deliver a poor match. However, characterizing and describing the SSP based on the identity of acoustically significant features is more effective and applicable to determining analogous areas.

Classifying or characterizing the SSP is not an easy task because the shape of SSPs is variable over the global region. However, there are distinct points in SSPs that are a common feature to most. While these points in the profile are common, their location on the profile changes. These distinct features, and other parameters derived from them, are important in analogous area determination as they directly affect sound propagation. The typical mid-latitude SSP in Figure 3 will serve as a guide for displaying the characterization parameters for an SSP.

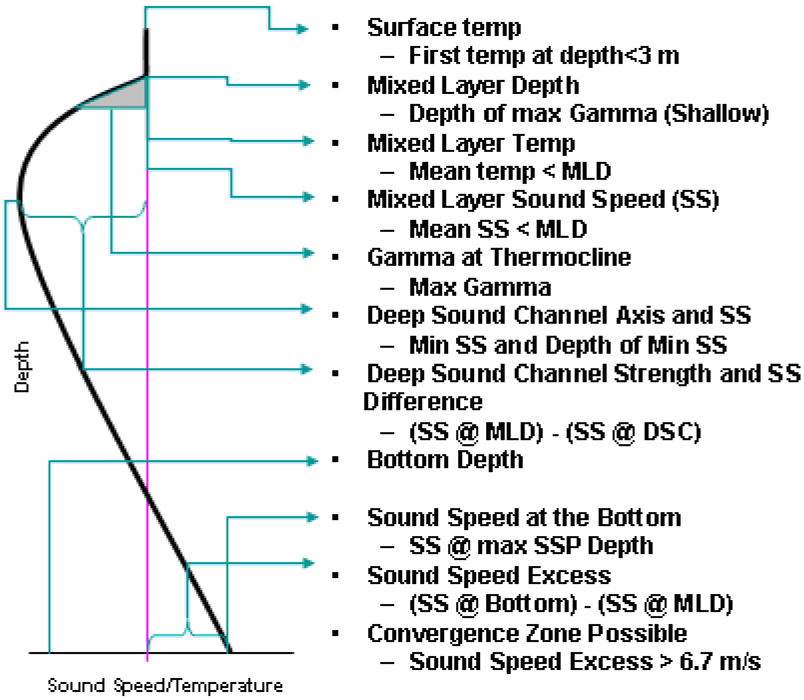

Figure 3. SSP Characterization Parameters. [After Everett, 2005, p. 25].

a. *Surface Temperature*

Surface temperature, referred to as Sea Surface Temperature (SST), is the shallowest temperature at the upper boundary of the ocean (<3m). SST plays a significant role in ASW operations, especially in shallow water where strong horizontal temperature variations occur over short distances, and is a major input into many oceanographic models. Convergence Zone (an area at or near the ocean surface where sound rays are focused, promoting increased sound levels) range determination is also affected by SST (NAVOCEANO, 1999, p. 39, 91, 93). Due to the acoustic importance of SST, it is included as one of the parameters used in locating analogous areas.

b. Mixed Layer Depth (MLD)

Mixed Layer Depth (MLD) is defined as the location of maximum near surface temperature and is also important in ASW operations. The Mixed Layer (above the MLD) is composed of isothermal water that is the result of wind action blowing across the ocean surface. Within the Mixed Layer, sound speed increases with depth due to increasing pressure. However, in areas of prolonged calm and sunny conditions, the Mixed Layer disappears as the higher surface temperature gives way to temperatures beneath that decrease with depth. The location of rapidly decreasing temperatures with depth is known as the thermocline. Sound speed decreases as temperature decreases in the upper profile of the ocean and the thermocline marks the location of decreasing sound speed with depth. The seasonal thermocline is well defined in summer and fall, when surface waters are warm, and becomes part of the surface layer in the winter and spring and also in the Arctic (Urick, 1983, p. 117). Figure 4 identifies the change in the Mixed Layer due to the season. Within the Mixed Layer, as previously mentioned, sound speed increases with depth. Because sound waves refract toward areas of lower sound speed, any sound emitted within the Mixed Layer tends to become trapped and can propagate long distances as it refracts upwardly within the layer and successively reflects off the sea surface. For this reason, MLD is an important parameter valuable to analogous area determination.

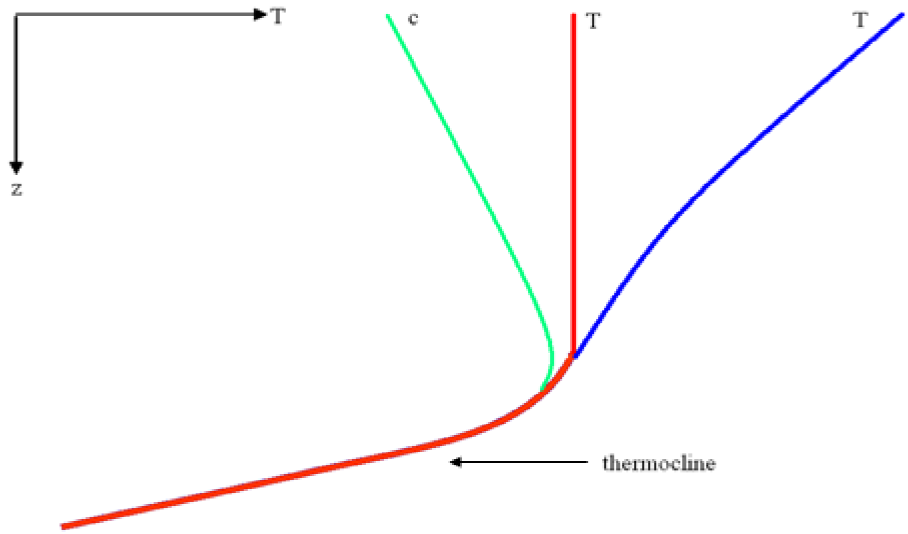

Figure 4. Example of Mixed Layer variation with season. The red line represents a well define mixed layer as would be found in winter and spring. The blue line shows the absence of a well defined mixed layer as would be found in summer and fall. The green line represents the sound speed, c, within the Mixed Layer [After Everett, 2005, p. 27].

Because of the acoustic significance of MLD and the Mixed Layer, modeling such features is important. Turbulent models exist that predict the MLD but difficulty arises when comparing the model-predicted MLD to observations (Kara et al., 2000, p. 16,803). The Naval Research Laboratory (NRL), in conducting the Mixed Layer Depth (NMLD) project, compiled monthly climatologies of MLD using an optimal definition of MLD determined from density profiles (NRL Code 7320, 2006). The NMLD climatology defines the Isothermal Layer Depth (ILD) as the depth where the temperature has deviated 0.8°C from the temperature at the 10m location. This criterion is capable of accommodating the variety of temperature profiles that exist globally. In areas where there is no significant salinity gradient, the same criterion is used for MLD determination. In such cases where a pronounced salinity gradient is present, the MLD is based on density variations from a temperature change in the equation of state. Statistical analysis and error testing have shown that the $\Delta T = 0.8°C$ criteria yield MLD results that are within 20m of observed data MLD in 85% of the cases (Kara et al., 2000, p. 16,819). LCDR Everett calculated the MLD using the same criteria, and inspection of MLD values compared to visual plots of SSPs revealed that accurate MLDs were calculated for SSPs having more than one profile point (Everett, 2005, p. 26). The MATLAB code written by LCDR Everett to determine MLD was used in this thesis but was modified to eliminate MLD values for single-point SSPs. At least two profile points (one at 10m and one beneath 10m) are needed to determine a deviation in temperature from the 10 m location.

The Mixed Layer Depth (MLD) can also be assumed to be the location at the top of the thermocline, where the maximum gradient or "Gamma" in the shallow portion of the SSP is located (Everett, 2005, p. 26). "Gamma" is defined as the rate of change of sound speed with depth (${}^{dSoundSpeed}\!/\!_{dDepth}$) and, in this thesis, describes the gradient within the thermocline.

c. Mixed Layer Temperature (MLT)

Mixed Layer Temperature (MLT) is the mean temperature within the Mixed Layer. While it does not have direct acoustic implications, it is one of the parameters that physically characterized the Mixed Layer and can affect the buoyancy control of submerged submarines operating in the surface layer.

d. Mixed Layer Sound Speed

Mixed Layer Sound Speed is the mean sound speed in the Mixed Layer for all points shallower than the MLD is used to compute other important acoustic parameters used in this thesis.

e. Gamma at the Thermocline

The thermocline is characterized by a negative temperature or sound speed gradient. Because temperature (sound speed) decreases rapidly over a small depth, it can be assumed that the thermocline will have the maximum Gamma in the SSP (Everett, 2005, p. 28).

f. Deep Sound Channel Axis (DSCA)

The Deep Sound Channel Axis (DSCA), also known as the Deep Sound Channel Depth (DSCD), is the point in the SSP having the minimum sound speed, and can vary from 1300 meters in the mid-latitudes to the near surface in polar waters. The sound speed gradient is zero at the DSCA, where temperatures decrease with depth from the warmer surface water temperatures (thermocline), giving way to a negative temperature and sound speed gradient. Below the DSCA, the temperature is nearly isothermal and sound speed increases as pressure increases. Here the sound speed gradient is positive. Thus, the DSCA is an inflection point in the SSP, where the gradient transitions from negative to positive.

The acoustic impact of the DSC, also called the Primary Sound Channel or SOFAR (Sound Fixing and Ranging) channel, was first realized in World War II when investigations began to determine a way to locate downed pilots. Investigators found that the properties of the DSC allowed sound transmission for thousands of miles and aviators' positions could be determined by triangulation as the time between the arrivals of explosive-generated sound, was measured at two or more locations (Urick, 1983, p. 159). Sound generated within the DSC travels such long distances due to refraction as sound bends toward lower sound speed. The sound essentially becomes trapped and undergoes little transmission loss as reflective losses from the surface and bottom are avoided. In the deeper oceans, the DSC plays a significant role in sound propagation and the DSCA is, therefore, a valuable parameter to use in analogous areas determination. Other valuable parameters can be derived from DSCA properties and will be discussed later.

g. Deep Sound Channel Sound Speed

The Deep Sound Channel Sound Speed is defined as the sound speed at the DSCA, where it is a minimum. This sound speed is used to calculate the Sound Speed Difference and the Deep Sound Channel Strength.

h. *Sound Speed Difference*

Sound Speed Difference is the difference in sound speeds of two points in the SSP. For the shallow water case, the Sound Speed Difference is the difference between the surface and bottom sound speeds and defines the strength of the surface half channel, where sound waves refract upward due to a positive gradient of sound speed. For deep water cases, the Sound Speed Difference is the difference between the sound speed in the Mixed Layer and DSC sound speed (Everett, 2005, p. 28). Sound Speed Difference is useful in determining the strength of sound channels, specifically the DSC strength, and is included in this thesis for that purpose.

i. *Deep Sound Channel Strength*

The strength of the DSC is a very important acoustic parameter that gives an indication of the maximum sound speed change that a given sound ray may encounter in the DSC. Mathematically, the DSC Strength is either the difference between the bottom and DSC sound speeds or the Sound Speed Difference defined above, whichever is smallest. In shallow water the sound speed at the bottom can be less than the Mixed Layer sound speed. In this situation, the DSC Strength is the difference of the bottom and DSC sound speeds. In deep waters where the bottom sound speed is larger than the Mixed Layer sound speed, the DSC Strength is the Sound Speed Difference. Figure 5 gives a more detailed view of DSC Strength. In profile A, a shallow water case, sound speed at the bottom is less than the Mixed Layer sound speed. In profile B, bottom sound speed is greater than sound speed in the Mixed Layer.

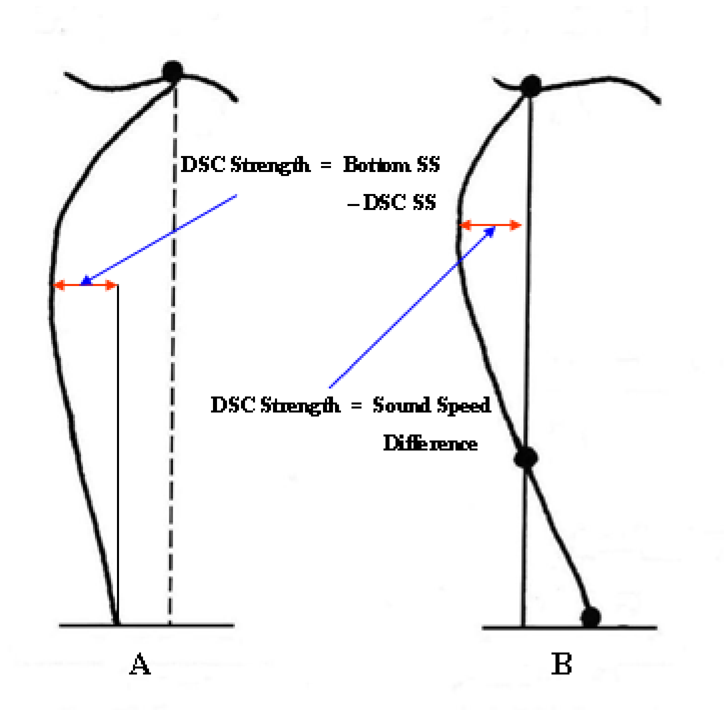

Figure 5. DSC Strength for (A) Shallow Water and (B) Deep Water. [After NAVOCEANO, 1999, p. 88].

j. Bottom Depth

Bottom Depth is a parameter that has significant importance in determining analogous areas. For deep water areas, bottom characteristics like sediment type and sediment thickness are less important than in shallow water areas where sound will undergo scattering, absorption, and reflection, contributing to much greater Transmission Loss (TL).

k. Sound Speed at the Bottom

Sound speed at the bottom of the ocean can be defined a number of ways. The simplest, and most obvious, is that it is the sound speed at the bottom boundary of the ocean. This can normally be taken from the SSP, however, some profiles do not extend to the bottom. In this situation, other methods can be used to extrapolate the sound speed (Everett, 2005, p. 29). If the last point in the profile is near the bottom, then linear interpolation using the sound speed gradient between the last two points would allow determination of the bottom sound speed. This method is adequate if the gradient is close to the pressure-dominated region gradient of $0.016s^{-1}$. However, in cases where the depth of the last point in the profile is not close to the bottom and the associated sound speed gradient is not near $0.016s^{-1}$, sound speed extrapolation is impossible. The data used in this thesis come from profiles that extend to the bottom, allowing sound speed to be calculated using the temperature and salinity values there. Had data that did not extend to the bottom been used, then the method of linear interpolation could have been used to determine sound speed at the bottom.

l. Sound Speed Excess

Sound Speed Excess is defined as the difference between the Mixed Layer sound speed and sound speed at the bottom and is an extremely important acoustic parameter in that it determines whether or not Convergence Zone (CZ) propagation is possible. For CZ propagation to exist there must be sufficient depth excess or sound speed excess. Depth excess is the difference between the Critical Depth and the bottom, where the Critical Depth is defined as the depth of the equivalent Mixed Layer sound speed located below the DSCA, as shown in Figure 6. Depth excess and sound speed excess are used interchangeable when discussing CZ propagation. For a near-surface source, a minimum depth excess of 200 fathoms (365.8m) or sound speed excess of 6.7 m/s is required for a 50% probability of CZ propagation. The probability increases to 80% if depth excess is greater than 300 fathoms (548.6m) or sound speed excess is greater than 10.1 m/s (NAVOCEANO, 1999, p. 90). Because Convergence Zones allow for the detection of distant contacts in deep water, Sound Speed Excess is used as a parameter for analogous area determination in this thesis.

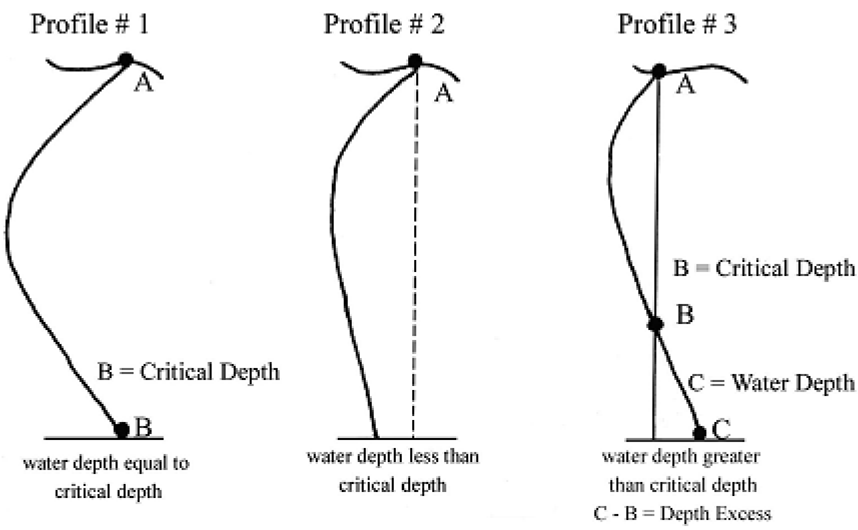

Figure 6. Sound Speed Profiles showing Critical Depth and Depth Excess. [From NAVOCEANO, 1999, p. 88].

C. BOTTOM CHARACTERISTICS

The ocean bottom is an important component in underwater acoustics because sound is subjected to scattering and absorption losses as it interacts with the bottom. These losses are more variable and complex than those that occur at the sea surface, due to diverse compositions and the presence of multiple layers, and are affected by the sediment properties (type, thickness, sound speed, density, porosity), frequency of the interacting sound wave, and the angle at which the sound waves strikes the bottom. None of these are equal at every location on the earth making acoustic modeling of the bottom complex.

Figure 7 relates the transmission and reflection of sound as it interacts in multiple layers having different properties. The top layer represents the ocean having a particular density, ρ, and sound speed, c. The two layers beneath represent layers of sediment that also have a unique ρ and c. Density and sound speed together describe the acoustic impedance of the medium and determine how much sound is reflected and transmitted to the adjacent layer. *T* and *R* in the diagram refer to the transmission and reflection coefficients, respectively, while the subscripts denote the layers that affect the ray.

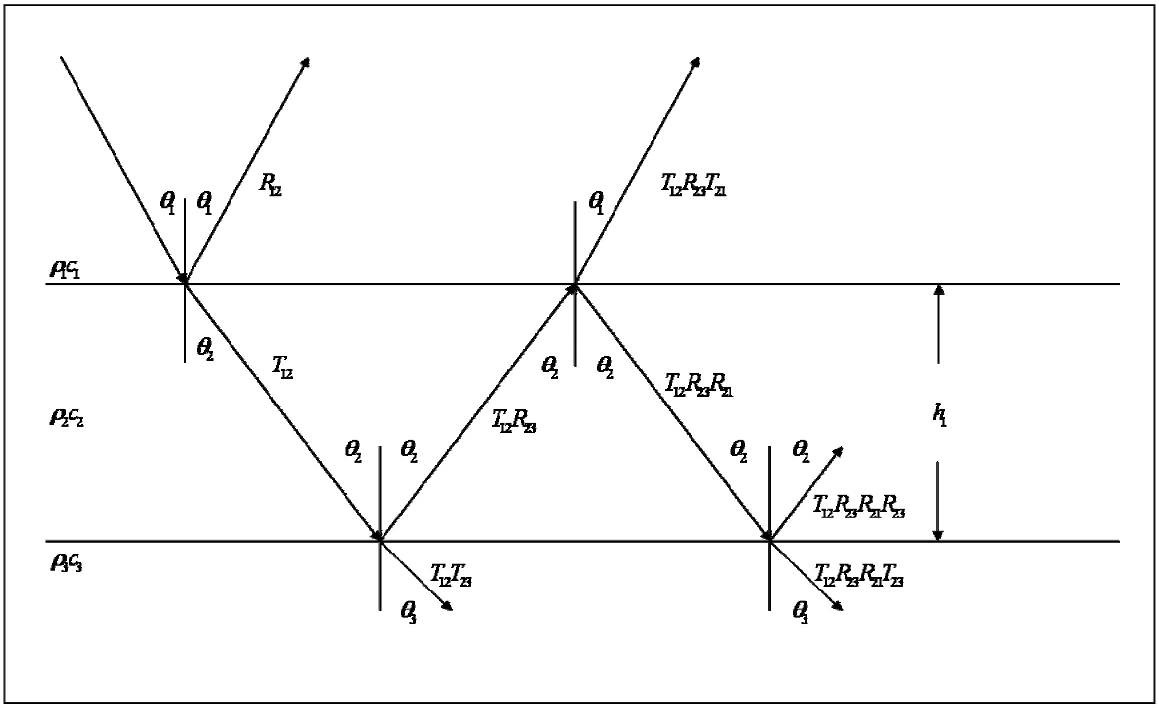

Figure 7. Example of reflection, *R*, and transmission, *T*, in different mediums. [From Everett, 2005, p. 31].

1. Sediment Type

Sediment type is an important parameter when examining and classifying the ocean environment because numerous types of sediments exist, each having different acoustical properties. One way of classifying the different bottom types is to categorize sediments based on the magnitude of their bottom loss (Urick, 1979, p. 10-10). Bottom loss curves have been constructed based on measured data, theory, and speculation, where bottom types are grouped into numbered categories based on the expected bottom loss with grazing (incidence) angle. The numbered categories correspond to CLASSIFIED bottom-classes that can be tied to different ocean areas. Because this thesis is UNCLASSIFIED, curves such as the one just described were not used, but other data exists that are useful for determining bottom losses for various bottom types. Future analogous area investigation would benefit from using available CLASSIFIED data. Figure 8 is an UNCLASSIFIED display of backscattering strength for various bottom types versus grazing angle. The backscattering strength is particularly useful in hunting for mines lying on the ocean floor (Urick, 1979, p. 10-10).

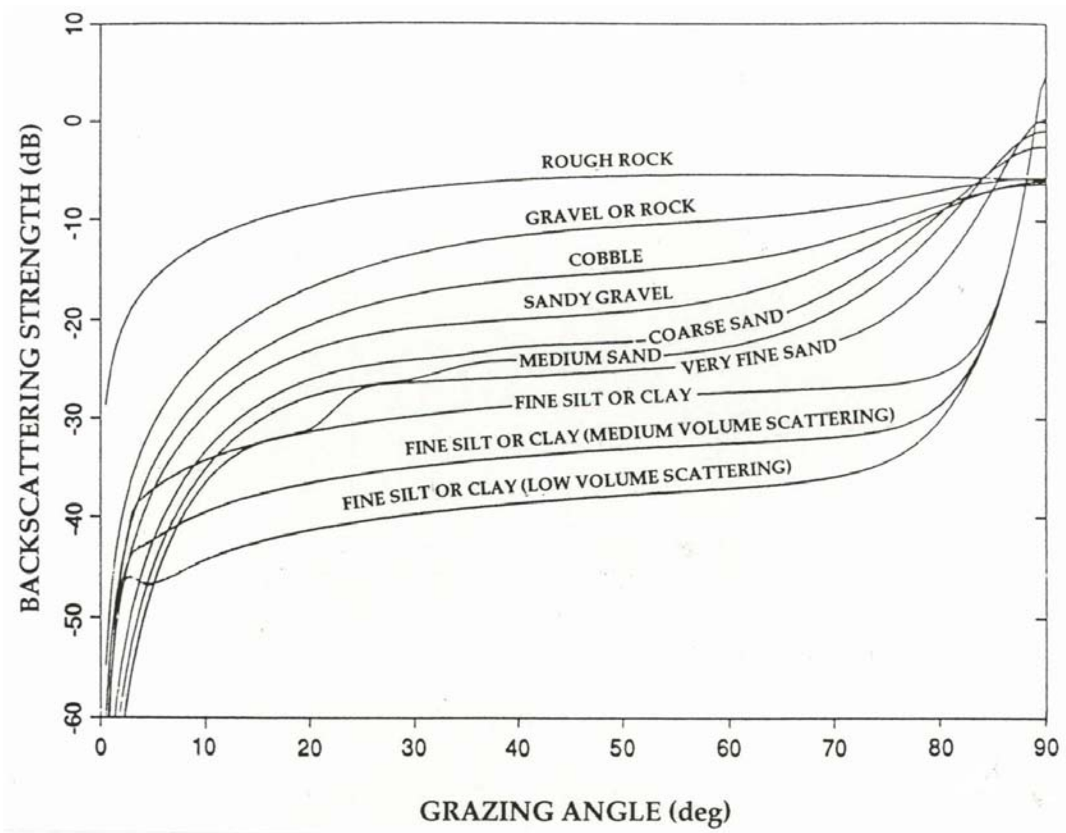

Figure 8. Backscattering Strength (dB) versus Grazing Angle (deg) for various Sediment Types. [From NAVOCEANO, 1999, p. 18].

2. Sediment Thickness

The thickness of sediment layers is particularly important in determining the amount of transmission and reflection that occurs within a layer. In Figure 7, h_1 refers to the sediment thickness of the layer and is used in calculating the total reflection and transmission. Databases exist that estimate sediment thickness, as representative of the depth to acoustic basement, and are the type of data used in this thesis.

3. Frequency and Grazing Angle

The amount of bottom loss in the ocean bottom is dependent on grazing angle and acoustic frequency. Generally, bottom loss tends to decrease with an increase in frequency and grazing angle. Low frequency sound will result in lower losses at all grazing angles due to the combination of refracted energy returned to the sediment-water interface and the smaller reflective losses at the bottom (NAVOCEANO, 1999, p. 17).

4. Density, Sound Speed, and Porosity

The single most important sediment property determining the acoustic characteristics is porosity (Urick, 1979, p. 10-7). However, there is a strong relationship between porosity, density, and sound speed and all three properties are, consequently, important. The density of a mixture of two mediums can be explained by the additive law that states any property of a mixture equals the sum of the properties of the components, separately. The equation for the density of a sediment mixture, based on numerous measurements on sediments is $\rho_{mix} = 2.68 - 1.65\beta$, where β is the porosity of the sediment (Urick, 1979, p. 10-4).

Laboratory experiments and in-situ data have been collectively used to develop an equation to closely approximate the sound speed in sediment (Urick, 1979, p. 10-4). The equation, $\nu = (\rho_{mix} k_{mix})^{-1/2} = [(\rho_w\beta + \rho_s(1-\beta))(k_w\beta + k_s(1-\beta))]^{-1/2}$, requires knowledge of the density of water (ρ_w) and sediment (ρ_s) and the compressibility of water (k_w) and sediment (k_s) to determine the sound speed. Using the formula, it can be predicted that the sound speed in sediments of high porosity (low density), such as mud, to be slightly less than the sound speed of the water above. Low porosity (high density) sediments like hard sand have sound speeds 10-20% higher than the overlying water.

The two sediment databases used in this thesis contain data that are based on sediment type, grain size, and thickness. Including additional sediment data is highly recommended for future study and analysis in analogous area determination.

D. AMBIENT NOISE

Ambient noise sources vary on a temporal and spatial scale. Understanding their contribution to the ocean background noise is paramount when engaging in USW exercises and operations. As mentioned previously, shipping, winds, waves, and rainfall are all environmental parameters that affect sonar performance in the ocean and should be included when developing a method for determining analogous areas. Curves, such as the one shown in Figure 9 showing the average deep-water ambient noise spectrum level, have been constructed to aid in the prediction of sonar performance.

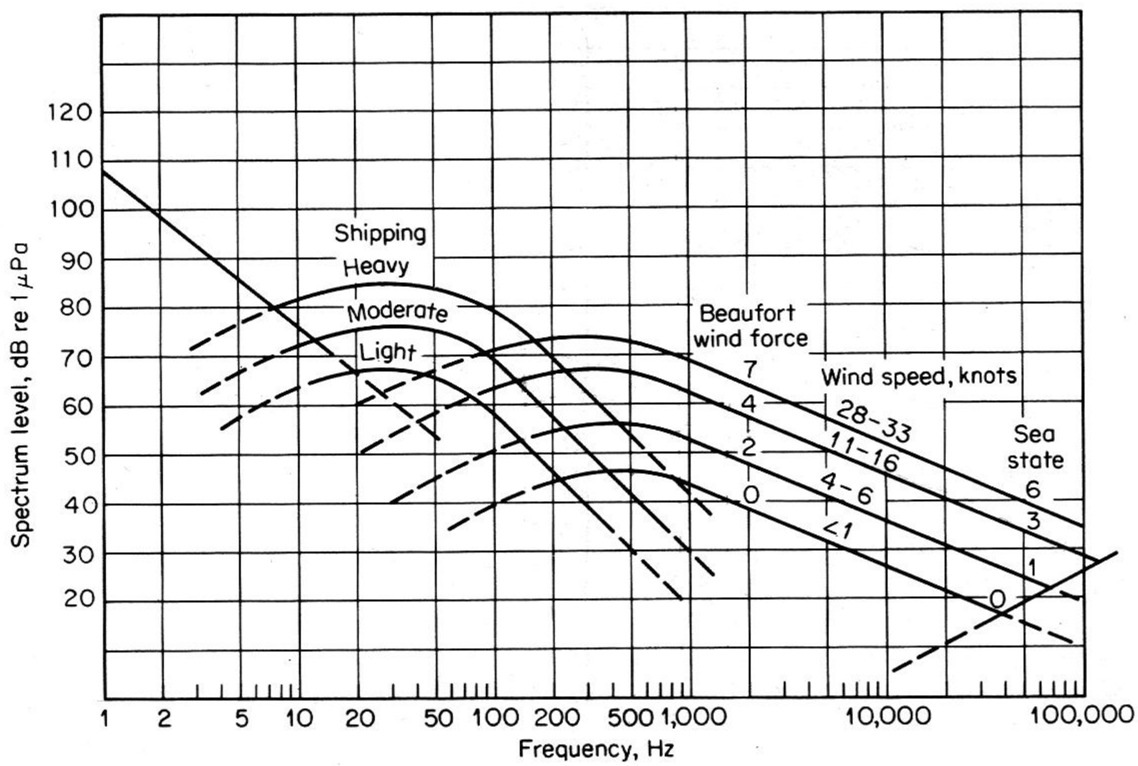

Figure 9. Average deep-water ambient noise spectra. [From Urick, 1983, p. 210].

1. Shipping

Ambient noise from ship traffic has been shown to dominate the noise spectrum at frequencies around 100 Hz, but can provide strong contributions to the frequency range of 30 Hz to 10 kHz (NAVOCEANO, 1999, p. 19). In order to fully understand the ambient noise produced from ships it is necessary to know the number of ships at any given point or area (shipping density) and its temporal variability, distance to ships, and the acoustic characteristics of different classes of ships. Databases exist that contain such information which could be useful in analogous area determination. The Historical Temporal Shipping (HITS) database is a NAVOCEANO database featuring shipping density by month, area, and ship type and was compiled using historical records of ship transits (Emery et al., 2001, p. 1). While not used in this thesis, due to regulations preventing its release to non-DOD (Department of Defense) agencies, it is recommended that future analogous area development include a historical shipping database like HITS.

2. Wind Speed and Wave Height

Wind speed and wave height have a significant impact in ocean acoustics and are responsible for dominant contributions to ambient noise level. Dominating the ambient noise spectrum from 300 Hz to 50 kHz, this sea-state related noise is generated from surface waves and winds and is considered to be the one of the most important ambient noise sources affecting active and passive sonar detection (NAVOCEANO, 1999, p. 24). The sea-state of the ocean is a description of the ocean surface in terms of observed wind and wave heights. While there is no instrument or sensor that measures the sea-state, Table 2 gives a physical description of the different sea states and the associated wind speeds and wave heights. Wind-generated noise level decreases with frequency below 300 Hz and increases with sea-state for all frequencies. At wave heights of 10 ft (3.05m) or greater, the generated noise level significantly reduces ASW operational effectiveness (NAVOCEANO, 1999, p. 20). Databases such as the Surface Marine Gridded Climatology database exist that contain climatological data of numerous ocean surface and meteorological parameters. Mean wind speed and mean wave height from this database were used in this thesis and will be discussed in the next section.

		WIND		ESTIMATING WIND SPEED		STATE OF THE SEA		
Beaufort Number	Descriptive Term	Mean Velocity (knots)	MPH	Effects Observed on Land	Effects Observed at Sea	WMO Code	Descriptive Term	Height (H 1/3) of waves in feet
0	Calm	1	1	Calm; smoke rises vertically	Sea like a mirror	0	Calm (Glassy)	0
1	Light Air	1–3	1-3	Direction of wind shown by smoke drift but not by wind vanes	Ripples with the appearance of scales are formed, but without foam crests			
2	Light Breeze	4-6	4-7	Wind felt on face/leaves rustle; ordinary vanes moved by wind	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break	1	Calm (Rippled)	0 –1/3
3	Gentle Breeze	7-10	8-12	Leaves and small twigs in constant motion, wind extends light flag	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses	2	Smooth (Wavelets)	1/3 – 1-2/3
4	Moderate Breeze	11-16	13-18	Raises dust and loose paper; small branches are moved	Small waves, becoming longer; fairly frequent white horses	3	Slight	1-2/3 – 4
5	Fresh Breeze	17-21	19-24	Small, leafy trees begin to sway; crested wavelets form on inland waters	Moderate waves, taking a more pronounced long form; many white horses are formed (chance of some spray)	4	Moderate	4 – 8
6	Strong Breeze	22-27	25-31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray)	5	Rough	8 – 13
7	Near Gale	28-33	32-38	Whole trees in motion; inconvenience felt when walking against wind	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of wind	6	Very Rough	13 – 20
8	Gale	34-40	39-46	Breaks twigs off trees; generally impedes progress	Moderately high waves of greater length; edges of crests begin to break into the spin-drift; the foam is blown in well-marked streaks along the direction of the wind			
9	Strong Gale	41-47	47-54	Slight structural damage occurs (chimney pots and slates removed)	High waves; dense streaks of foam along the direction of the wind; crests of waves begin to topple, tumble, and roll over; spray may affect visibility			
10	Storm	48-55	55-63	Seldom experienced inland; trees uprooted; considerable structural damage occurs	Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; on the whole, the surface of the sea takes a white appearance; the tumbling of the sea becomes heavy and shocklike, visibility affected	7	High	20 – 30
11	Violent Storm	56-63	64-72	Very rarely experienced; accompanied by widespread damage	Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind the waves); the sea is completely covered with long white patches of foam lying along the direction of the wind; everywhere the edges of the wave crests are blown into froth; visibility affected	8	Very High	30 – 45
12	Hurricane	64 and over	73 and over		The air is filled with foam and spray; sea completely white with driving spray; visibility very seriously affected	9	Phenomenal	over 45

Table 2. Description of sea-state, wind speed and wave heights. [From NAVOCEANO, 1999, p. 23].

An important aspect in analogous area determination is finding and utilizing available data of the parameters discussed in this chapter. The next section discusses the databases used to obtain the data that were utilized to perform analogous area determination in this thesis.

E. DATA SOURCES

In the development of the analogous area determination tool for this thesis it was important to use data that was accessible, in a modifiable format, that had extensive global coverage, and, most importantly, considered essential in modeling the acoustic environment of the ocean. Numerous databases exist whose data would be beneficial in including in the process, but only those that were unclassified and met the criteria above were selected. Adding classified data would provide additional information and is highly recommended for future additions. Because the method of analogous area determination used in this thesis is based on the capabilities of ArcMap GIS software (discussed in Chapter III), the addition of supplementary "layers" of data is straightforward, making expansion of this process uncomplicated. As more data becomes available and is incorporated, the degree of usefulness of this tool will be greatly enhanced.

1. Sound Speed Profiles

a. Generalized Digital Environmental Model (GDEM-V)

The Naval Oceanographic Office (NAVOCEANO) has constructed a climatological database that provides gridded monthly means and standard deviations of global ocean temperature and salinity versus depth.

The current GDEM-V database, version 3.0, has a resolution of 15 arc-minutes of latitude and longitude, an improvement over the previous version having 30 arc-minutes resolution. The database is constructed with sufficient vertical and horizontal resolution to be useful in many USN applications of ocean modeling and acoustics. The data span the global oceans with a latitude range of 82.0°S to 90.0°N (689 points) and longitude range of 0° to 359.75° (1440 points), including freshwater lakes and landlocked seas (e.g. Great Lakes). While the GDEM-V database is UNCLASSIFIED, classified data were incorporated in its construction. The content for the GDEM-V database comes from data extracted from the 1995 Master Oceanographic Observation Data Set (MOODS), having nearly eight million profiles of temperature and salinity (NAVOCEANO, 2003a, p. 1, 3-5).

Four GDEM-V CD-roms from NAVOCEANO contain 48 files for temperature and salinity profile information and one file for bottom depth, stored in Network Common Data Format (NetCDF). The 48 profile files are divided such that each contain monthly information for a certain parameter (temperature, salinity, temperature standard deviation, and salinity standard deviation). For each parameter/monthly file, latitude, longitude, depth and value of the parameter are given. Values over land or underground are assigned a special value (-32000). The one bottom depth file contains values for latitude, longitude, and depth (gridded in 78 nodes corresponding to depths in meters) (NAVOCEANO, 2003a, p. 1, 4-5). The CDs also contain computer programs written in FORTRAN to extract the data from the NetCDF files but a MATLAB program was used in this thesis to extract the required data. Because the data are gridded, global, and in a well defined format, its selection for use in this thesis is ideal over other temperature and salinity databases.

2. Wind Speed and Wave Height

Ambient noise sources are extremely important in trying to detect a target in the ocean. Having access to data such as wind speed and wave height is, therefore, necessary in order to develop an accurate analogous area determination tool. Several UNCLASSIFIED databases exist that provide such information.

a. Surface Marine Gridded Climatology (SMGC)

Fleet Numerical METOC Detachment Asheville Climatology Center maintains a particular database of sea surface climatology data. The Surface Marine Gridded Climatology (SMGC) database was developed to provide data describing the environment at the air-ocean interface. It began in the late 1960s when the National Climatic Data Center (NCDC) combined the 17 different marine data sets that it maintained into one database. This database was then used to construct the U.S. Navy Marine Climatic Atlases of the World. A decade later, several organizations collaborated to continue the consolidation of a marine database. Out of this effort came the Comprehensive Ocean-Atmosphere Data Set (COADS). The original 17 data sets were supplemented with data taken from more recent ship Global Telecommunication System (GTS) data and in-situ data. Out of the desire to produce an interactive marine climatology product, SMGC versions 1.0 and 2.0 were derived from COADS. SMGC version 1.0 contained mean and standard deviations for six parameters, an eight-point wind compass rose, and frequency of occurrence of icing potential and gale force winds (Fleet Numerical METOC Detachment Asheville, 2000, p. 4). SMGC version 2.0, an all-encompassing database including all the major synoptic surface observations, is now the current version.

SMGC 2.0 provides greater global coverage than version 1.0 and includes data from 1854-1997. Like version 1.0, the data is gridded at 1.0° latitude and longitude and organized by month (Fleet Numerical METOC Detachment Asheville, 2000, p. 7). While version 2.0 contains 17 ship observation parameters (Air-Sea ΔT, Air Temperature, Ceiling Height, Relative Humidity, Pressure, Sea Surface Temperature (SST), Swell Direction, Swell Height, Swell Period, Total Cloud Cover, Visibility, Wave Direction, Wave Height, Wave Period, Weather, Wind Direction, Wind Speed) and their statistics, only mean wave height and mean wind speed were used in this thesis because of their acoustic relevance to analogous area determination. These data originated from version 1.0 because the ASCII format of the data in that version allowed for easier processing over the binary format of version 2.0 and are similar enough to version 2.0 for the purpose here.

3. Sediment Thickness

The National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA) has compiled a database of total sediment thickness of the global oceans and seas. These data are easily downloadable in either NetCDF format, ASCII format, or an ArcGIS file, open source from http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html. The sediment thickness data are gridded at a resolution of five arc-minutes by five arc-minutes. The data were collected from three principal sources: isopach (lines of equal thickness) maps, ocean-drilling results, and seismic reflection profiles maintained by NGDC. In the process of compiling the database, the isopach maps were first digitized, then algorithmically gridded. The values of the data are in meters (m) and represent the depth to the acoustic basement (Divins, 2008). Because ArcGIS software is used in the process of determining analogous areas for this thesis, the ArcGIS shapefile (.shp) was chosen as the best file option.

4. Sediment Type

An UNCLASSIFIED sediment type database was necessary for use in this thesis to make the analogous area determination tool as comprehensive as possible. The chosen database, NAVOCEANO's Surface Sediment Type database, was easy to acquire and provided adequate spatial coverage and sediment type classification.

The Surface Sediment Type database describes the sediment types by assigning integer values which correlate to a particular sediment type. These integer descriptors consider the grain size, origin, and placement of the sediment (NAVOCEANO, 2003b, p. 3). The database contains both high and low resolution data, at 6-seconds and 5-minutes, respectively. The high resolution data, restricted to selected geographical areas, were obtained from analyses of sediment grabs and cores collected by NAVOCEANO, National Imagery and Mapping Agency (NIMA) charts, side scan imagery, and from bathymetric and seismic publications. The 5-minute low resolution data cover a majority of the global oceans and seas from a latitude of approximately 50°S to approximately 75°N, as shown in Figure 10, and was assembled from various high-level sources, including maps, atlases, and regional ocean basins studies.

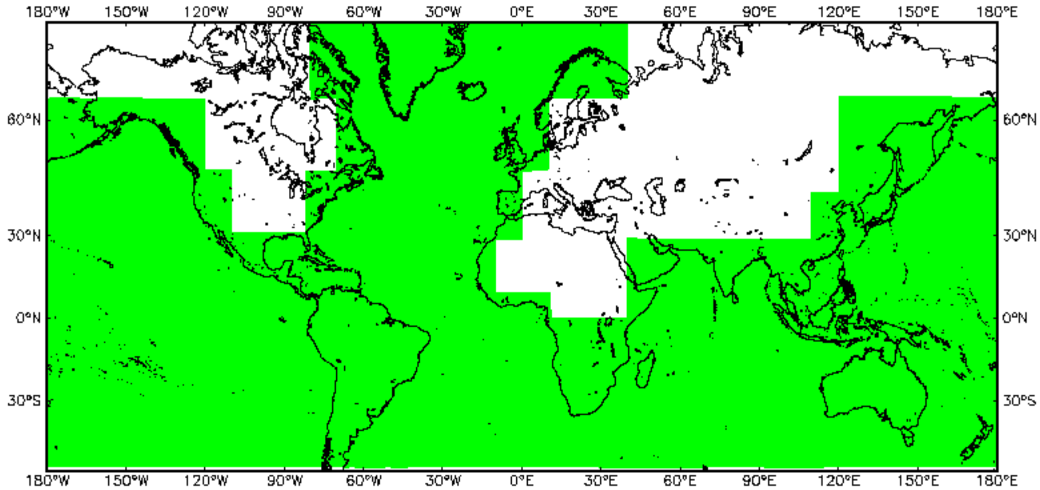

Figure 10. World-wide 5-minute geographic coverage of the Surface Sediment Type database. Locations with no data or over land are shown in white. [From NAVOCEANO, 2003b, p. 6].

Data are provided in four different files: Enhanced, Standard, Reduced, and High Frequency Environmental Acoustics (HFEVA). The Enhanced data file is a set of over 400 sediment categories suitable for use by geologists. The Standard data file is a reclassification of the Enhanced data, containing 30 sediment grain-size and sediment-mixture categories, suitable for use when a full spectrum of sediment types having a comprehensive arrangement is desired. The Reduced set, like the Standard set, is a reclassification of the Enhanced set. Having a simpler organization of only 15 categories, this file is most appropriate for geologists and engineers having knowledge of the Wentworth grain-size scale. Finally, the HFEVA data are divided into 23 "standard sediment types" based on grain size and sediment mixture, corresponding to six geo-acoustic parameters. These six parameters are inputs into the Comprehensive Acoustic Simulation/Gaussian Ray Bundle (CASS/GRAB) acoustic performance model (NAVOCEANO, 2003b, p. 4). Because the categorization of the HVEVA dataset is based on acoustical properties rather than physical properties alone, it was chosen for use in this thesis. The data were obtained from NAVOCEANO in the form of shapefiles (.shp) easily imported into ArcMap software. Table 3 contains the 23 sediment types used in the HFEVA file. The 23 sediment types are grouped into 12 categories for the global 5-minute lower resolution set.

HFEVA Standard Sediment Type	HFEVA Category
Rough Rock	1
Rock	2
Cobble or Gravel or Pebble	3
Sandy Gravel	4
Very Coarse Sand	5
Muddy Sandy Gravel	6
Coarse Sand or Gravelly Sand	7
Gravelly Muddy Sand	8
Medium Sand or Sand	9
Muddy Gravel	10
Fine Sand or Silty Sand	11
Muddy Sand	12
Very Fine Sand	13
Clayey Sand	14
Coarse Silt	15
Gravelly Mud or Sandy Silt	16
Medium Silt or Sand-Silt-Clay	17
Sandy Mud or Silt	18
Fine Silt or Clayey Silt	19
Sandy Clay	20
Very Fine Silt	21
Silty Clay	22
Clay	23
No data	*888*
Land	*999*

Table 3. HFEVA Sediment Types. [From NAVOCEANO, 2003b, p. 40-41].

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III. DATA ANALYSIS, ACQUISITION, AND MANIPULATION

An ideal analogous area determination tool would be robust, easy to use, and be applicable to a variety of missions. For example, a MIW-driven scenario should not return the same analogous areas as a scenario involving an open-ocean ASW operation because the data parameters important to a MIW mission are different from the parameters that would be used in an ASW deep water mission. Prior approaches to tool development included processes to adjust the weights of parameters used to determine analogous area based on target area location and mission type. However, these methods do not give the user full control of modifying the tool to suit their needs. The analogous area tool developed in this thesis allows users to determine what parameters are important to the mission or operation and grant them the flexibility and discretion to determine the amount of similarity required to accomplish mission training.

Because the process involved is as important as the results in analogous area determination, an in-depth description is necessary to provide the rationalization and steps involved in creating the tool. The flowchart in Figure 11 provides a visual overview of the analogous area determination process. The pages that follow provide the detail associated with the first five blocks of the flowchart. The final block, "Perform Query to Determine Analogous Areas," is most important to the tool user and is detailed in Chapter IV. A specific example is used to showcase and validate the process.

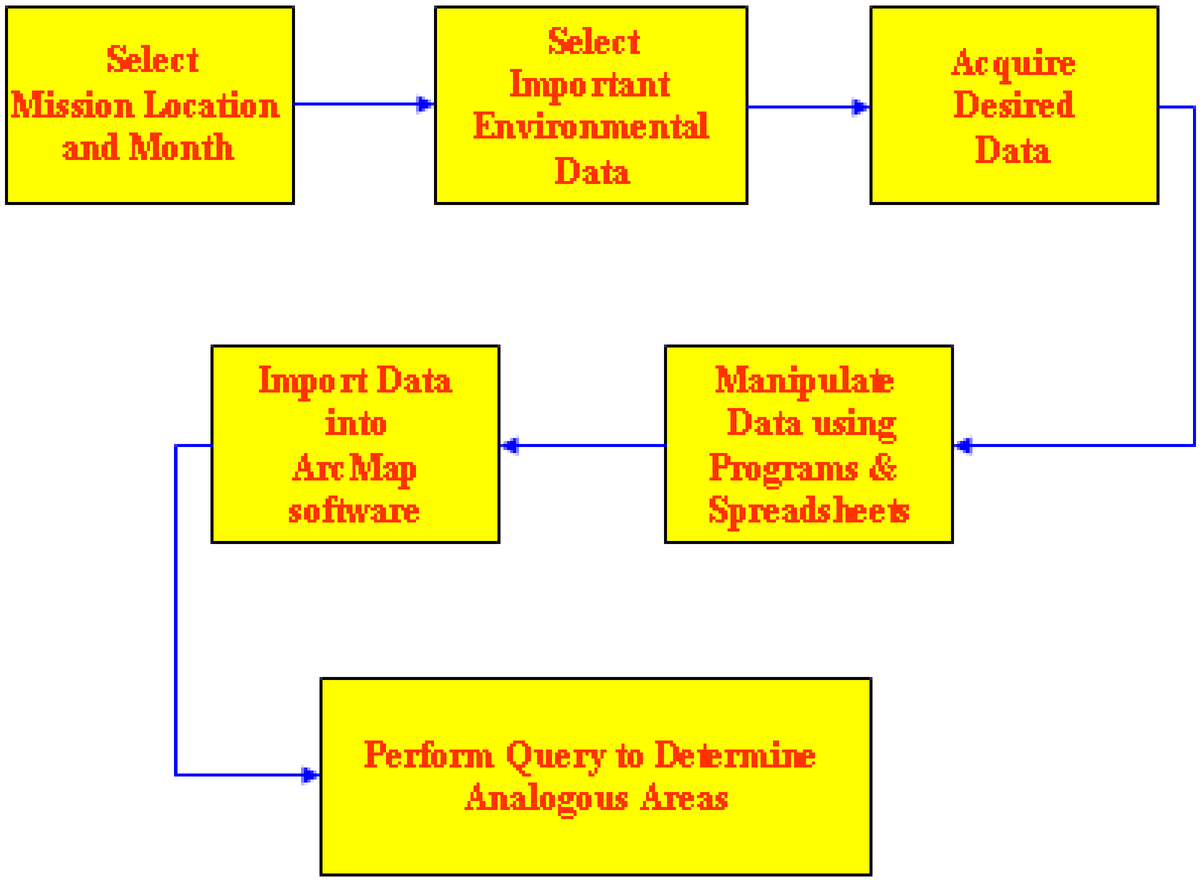


Figure 11. Flowchart of Analogous Area Determination Process.

A. SELECT MISSION LOCATION AND MONTH

The “target area” is defined as the location where the mission is to be performed and the “source area” refers to the locations from which analogous areas will be selected. The first step in the process of finding analogous areas is to determine the location of the target area and the month of year such actions will take place. In the previous analogous area tools, only pre-selected areas (chosen by tool developer with no user option to select additional locations) were chosen as the target or source areas. Mr. Miyamoto’s ESA (Miyamoto, 1999) contained only 28 pre-selected areas, evenly split between target areas outside CONUS (OCONUS) and source areas in CONUS. No variation in time of year for the data used was taken into account. LCDR Everett, in “USW Area Analogs,” increased the source area size from which analogous sites could be selected from 14 locations in CONUS (ESA) to tens of thousands of source areas in or near US Fleet Training Areas and data was separated by month for both the target and source areas (Everett, 2005, p. 42). Only data for two different target areas were extracted and having pre-selected source areas was useful in the fuzzy logic approach described in Chapter I. However, more source areas from which analogous areas could be found would affect the fuzzy set membership determination since fuzzy membership was based on parameter ranking by percentile within the source areas. Adding more source areas would change the percentile ranking of parameters and therefore, fuzzy entropy and match score would change. Mission and exercise locations vary, determined by planners and senior leadership, and limiting target area selection reduces the usefulness. It is also important for the data used to be temporally grouped (i.e. monthly) in order to provide the best time of year to train in the analogous area. To make this analogous area tool as practical and accurate as possible, global coverage of most or all of the data are used and are temporally spaced on a monthly scale.

The target location used in the example in this chapter is in the South China Sea between Luzon and the continental shelf in January, at Latitude 20 degrees North and Longitude 119 degrees East. This same deep-water location was also used in LCDR Everett’s thesis (Everett, 2005, p. 51).

Once the target area and month of the operation are identified by planners, the next step in the process is to select the important environmental data to be utilized in the analogous area search tool. This step has significant implications for the analogous area search and will be discussed next.

B. SELECT IMPORTANT ENVIRONMENTAL DATA

To make the analogous area tool as beneficial as possible, proper analysis of the mission environment (target area) is necessary to ensure that data useful for comparison is properly chosen. The importance of the SSP has already been mentioned; the SSP has significant acoustic relevance in determining analogous areas and should always be a selected as a source for area comparison, independent of the mission location. If the entire ocean were a constant depth and every location at every time of year had the same profile, its use for comparison would be of no benefit. However, SSPs are variable and provide an array of information, when characterized, that is useful in describing the acoustic and physical ocean that can be used in the analogous area tool. Individual SSP characterization descriptors can be selected according to mission type and is discussed in Chapter IV.

Because the ocean is bounded by two media (atmosphere and bottom sediment), the interactions at these interfaces contribute to the sound characteristics within the water column. Like the SSP, an effective analogous area tool should include bottom and sea-surface parameters for use in the comparison process. These parameters provide inputs into the Transmission Loss (TL) and ambient noise portion of the Noise Level (NL) in the sonar equations, whose output estimates sonar performance.

For the example used here, the important variables chosen were the SSP descriptors (individual selection determined by mission), bottom sediment type and thickness, and wind speed and wave height. After selecting the important data sets, the next step in the process is the acquisition of the relevant data containing these variables.

C. ACQUIRE DESIRED DATA

Data acquisition to meet the needs of the analogous area tool used in this thesis requires knowledge of current databases, mostly maintained by NAVOCEANO. In addition to those discussed in Chapter II, various sources exist that can provide the necessary data, but the databases selected for use here meet the criteria required for analogous area determination in physical and acoustic terms.

1. Sound Speed Profile

As discussed in Chapter II, the temperature and salinity data located in the GDEM-V database provides excellent coverage and adequate resolution to use to determine sound speeds for SSP characterization. Since the file obtained from NAVOCEANO was formatted in NetCDF files, it was necessary to write MATLAB code to ingest the data. The code was written such that each monthly temperature and salinity file could be called into the program by changing the monthly variable to the number corresponding to the 12 months (i.e. 1-January, 2-February, 12-December). The temperature and salinity files were assigned to variables whose content was a 3-dimensional (3-D) (latitude, longitude, depth) matrix containing the global values for the variable. The one GDEM-V bottom depth file was imported via the same method, although the values stored in the assigned variable were not affected by altering the month. Once the monthly data files have been ingested into MATLAB, the same program calls a *function* program, previously written by CDR D. Benjamin Reeder, USN, in which the speed of sound is calculated using the Del Grosso equation. These sound speed values can be used for SSP characterization, which is discussed later.

2. Wind Speed and Wave Height

The wind speed and wave height data from the Surface Marine Gridded Climatology (SMGC) were available for use in ASCII format allowing easy importation into MATLAB via a simple program. Each monthly file was easily distinguishable from other monthly files through the use of a number suffix corresponding to the month. The four parameters used (mean wind speed, mean wave height, wind speed standard deviation, wave height standard deviation) were assigned variable names that required additional manipulation.

3. Sediment Thickness

Sediment thickness data from the National Geophysical Data Center (NGDC) was available in three file types as listed Chapter II. Because the ultimate destination for all data used in the analogous area determination is ArcMap, the ArcGIS shapefile (.shp) was simply downloaded from the open source website for later importation into the software. Unlike the GDEM-V and SMGC data, the Global Sediment Thickness data required no computer program for ingestion and manipulation. The importing of this data into the ArcMap software will be discussed in section E.

4. Sediment Type

NAVOCEANO's Surface Sediment Type database was available in four different types (Enhanced, Standard, Reduced, High Frequency Environmental Acoustics (HFEVA)) but for reasons discussed in Chapter II, the HFEVA data was chosen as the most applicable version for use in acoustical applications. The data was available in a shapefile (.shp) that, like the sediment thickness data, could be easily loaded into the ArcMap software without manipulation.

D. MANIPULATE DATA

The data manipulation required for the analogous area tool in this thesis involved the use of not only MATLAB but also Microsoft Office Excel as an intermediate tool to place data into the format required for importing into ArcMap. The details of the process involved in the data manipulation follow, with each data set given a separate section since the required manipulation was different in most of the cases.

1. Sound Speed Profile

Once the temperature and salinity data were imported into MATLAB and sound speeds calculated, it was necessary to accurately determine the SSP descriptive parameters discussed in Chapter II, mathematically. The program utilized for ingesting the data into MATLAB contained additional code for mathematically determining values for the descriptive parameters. Because MATLAB has the capacity to handle large amounts of data and process them rapidly, a *for* loop was generated allowing the program to calculate SSP characterization parameter values for each latitude (689 points) and longitude (1440 points) point not on land for an entire month before terminating. Points on land were assigned a “flag” value of “-32000” in GDEM-V and this program was coded to calculate only the descriptive parameters for points not on land.

The descriptive parameters for the SSP and their calculation method are as follows:

Latitude: A latitude value is contained in each SSP when sound speed is calculated from the 3-D temperature and salinity files. Each specific latitude can easily be “called” when the *for* loop runs through all latitudes.

Longitude: Longitude values are determined from the same method as latitude.

Isovelocity: Isovelocity is a binary descriptor for the entire SSP sound speed. An SSP is considered isovelocity if sound speed standard deviation is less than 0.8. This value was determined to provide an adequate isovelocity description based on SSP profiles having less than a 3 m/s range in sound speed. An SSP determined to be isovelocity is assigned a value of 1 and assigned a 0 otherwise.

Upward Refracting: An SSP having a positive gradient everywhere in the profile is defined as upward refracting and is assigned a binary value of 1 for upward refracting or 0 otherwise. The gradient in an SSP can easily be calculated in MATLAB by determining the slope of the line between successive points.

Downward Refracting: An SSP having a negative gradient everywhere in the profile is defined as downward refracting. Downward refracting profiles are assigned a binary value of 1 and those not downward refracting, having any positive gradient, are assigned a value 0.

No Deep Sound Channel: If the gradient is always negative below the MLD, then there is no DSC and this binary descriptor is assigned a value of 1. Any profile with a DSC is assigned a 0 value.

Surface Temperature: The first temperature in the profile is assigned as the Surface Temperature.

Mixed Layer Depth (MLD): MLD is calculated using the Navy Mixed Layer Depth (NMLD) project method of defining the MLD as the depth where the temperature deviates more than 0.8°C from the temperature at 10 m. This criterion was used to calculate MLD in LCDR Everett's thesis and provided accurate MLDs based on visual inspection of plotted SSPs (Everett, 2005, p. 48).

Mixed Layer Temperature (MLT): MLT is calculated by taking the mean of temperatures at depth intervals above the MLD.

Mixed Layer Sound Speed: The Mixed Layer Sound Speed is calculated by taking the mean of the sound speed at depth intervals above the MLD.

Gamma in the Thermocline: The gradient in the SSP with maximum absolute value is assigned to Gamma in the Thermocline (Everett, 2005, p. 48).

Deep Sound Channel Depth (DSCD): The DSCD is the depth in the SSP where sound speed is a minimum.

Deep Sound Channel Sound Speed: The minimum sound speed in the profile is Deep Sound Channel Sound Speed.

Sound Speed Difference: Sound Speed Difference is the difference between the Mixed Layer and DSC sound speeds. If there is no DSC or the profile is isovelocity then the Sound Speed Difference is the difference between the Mixed Layer and bottom sound speeds.

Deep Sound Channel Strength: The Deep Sound Channel Strength is either the difference of the DSC and bottom sound speeds or the Sound Speed Difference, whichever is smaller.

Sound Speed Excess: The bottom sound speed minus the Mixed Layer sound speed is the Sound Speed Excess.

Bottom Depth: GDEM-V assigns the last recorded depth as the “max depth” and this value is assigned to the Bottom Depth.

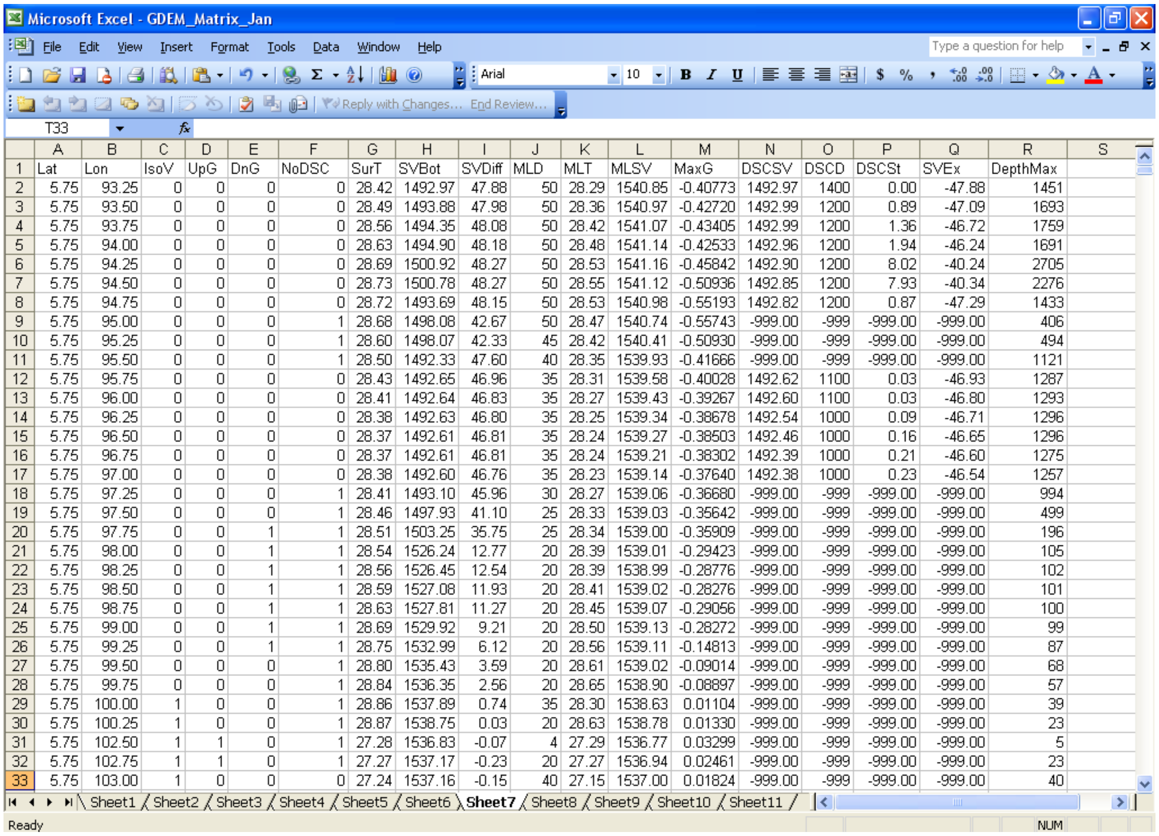
Bottom Sound Speed: The sound speed calculated from the temperature and salinity values at the last recorded depth, which is the bottom depth for GDEM-V data, is assigned the Bottom Sound Speed.

The program code was written to encompass all SSP conditions. If an SSP was found not having a MLD or DSCD, then all parameters associated with them were assigned “-999,” serving as a “flag” for ArcMap. Additionally, a profile containing only one point had all descriptors except Latitude, Longitude, Surface Temperature, Bottom Sound Speed, and Bottom Depth assigned “-999”. If an isovelocity condition was assigned to an SSP, then the MLD was set to the bottom and all Mixed Layer parameters set to define the entire SSP (Everett, 2005, p. 49).

As the descriptive parameters of the SSP for each latitude and longitude are calculated, the 18 descriptors are added as a row to a matrix. When all latitude and longitude SSP descriptors have been calculated, the entire matrix is formatted and saved as a text (.txt) file. The monthly text files contain the SSP descriptors for all latitude and longitude GDEM-V points not on land. Iterations of the process were run for each month and a total of 12 text files, each containing the descriptors for over 690,000 points and sized at approximately 84 megabytes, were generated.

The required file format for importing the SSP descriptor files into ArcMap is dBase (.dbf). MATLAB, however, cannot export .dbf files and an intermediate step was required to convert the text files into dBase files. This manipulation was performed in Microsoft Excel which also has the capacity to handle significant amounts of data. Text files (.txt) can easily be imported into an Excel workbook, but each worksheet in a workbook can only accommodate 65,536 rows of data. Microsoft Excel was used in LCDR Everett’s thesis for the same purpose of converting text files into dBase files (Everett, 2005, p. 57). Because those files contained a significantly smaller number of points than the files generated in this thesis, importation of each file into one worksheet was possible. As previously mentioned, each monthly SSP descriptor text file generated in MATLAB contained over 690,000 points (rows) and could not be ingested into an Excel worksheet all at once. In order to accommodate the large files, an additional program was coded and used to separate each monthly descriptor file into individual text files containing 65,535 rows of data. The individual files were specifically generated to include only 65,535 (one less than the maximum Excel worksheet limit) rows of data to allow for one row of header information in each worksheet. The separation program ran until all points in an SSP descriptor text file were accounted for. After separating each monthly file, 11 Excel worksheets were needed to hold all the data for one monthly descriptor file.

Each individual text file was imported into an Excel spreadsheet, one at a time, until all 11 files were included. Header information was input to identify the descriptive parameters. Figure 12 is a graphic displaying one Excel spreadsheet after an individual sheet has been imported. Number formatting of each column of data was then performed in order for all values to be recognized by ArcMap. Excel file types, .xls, are not recognized by ArcMap and, therefore, each sheet was saved as a dBase IV (.dbf 4) file. The data manipulation process was completed for all 12 monthly .txt files, ready to be imported into ArcMap.



Microsoft Excel - GDEM_Matrix_Jan

1	Lat	Lon	IsoV	UpG	DnG	NoDSC	SurT	SVBot	SVDiff	MLD	MLT	MLSV	MaxG	DSCSV	DSCD	DSCSt	SVEx	DepthMax
2	5.75	93.25	0	0	0	0	28.42	1492.97	47.88	50	28.29	1540.85	-0.40773	1492.97	1400	0.00	-47.88	1451
3	5.75	93.50	0	0	0	0	28.49	1493.88	47.98	50	28.36	1540.97	-0.42720	1492.99	1200	0.89	-47.09	1693
4	5.75	93.75	0	0	0	0	28.56	1494.35	48.08	50	28.42	1541.07	-0.43405	1492.99	1200	1.36	-46.72	1759
5	5.75	94.00	0	0	0	0	28.63	1494.90	48.18	50	28.48	1541.14	-0.42533	1492.96	1200	1.94	-46.24	1691
6	5.75	94.25	0	0	0	0	28.69	1500.92	48.27	50	28.53	1541.16	-0.45842	1492.90	1200	8.02	-40.24	2705
7	5.75	94.50	0	0	0	0	28.73	1500.78	48.27	50	28.55	1541.12	-0.50936	1492.85	1200	7.93	-40.34	2276
8	5.75	94.75	0	0	0	0	28.72	1493.69	48.15	50	28.53	1540.98	-0.55193	1492.82	1200	0.87	-47.29	1433
9	5.75	95.00	0	0	0	1	28.68	1498.08	42.67	50	28.47	1540.74	-0.55743	-999.00	-999	-999.00	-999.00	406
10	5.75	95.25	0	0	0	1	28.60	1498.07	42.33	45	28.42	1540.41	-0.50930	-999.00	-999	-999.00	-999.00	494
11	5.75	95.50	0	0	0	1	28.50	1492.33	47.60	40	28.35	1539.93	-0.41666	-999.00	-999	-999.00	-999.00	1121
12	5.75	95.75	0	0	0	0	28.43	1492.65	46.96	35	28.31	1539.58	-0.40028	1492.62	1100	0.03	-46.93	1287
13	5.75	96.00	0	0	0	0	28.41	1492.64	46.83	35	28.27	1539.43	-0.39267	1492.60	1100	0.03	-46.80	1293
14	5.75	96.25	0	0	0	0	28.38	1492.63	46.80	35	28.25	1539.34	-0.38678	1492.54	1000	0.09	-46.71	1296
15	5.75	96.50	0	0	0	0	28.37	1492.61	46.81	35	28.24	1539.27	-0.38503	1492.46	1000	0.16	-46.65	1296
16	5.75	96.75	0	0	0	0	28.37	1492.61	46.81	35	28.24	1539.21	-0.38302	1492.39	1000	0.21	-46.60	1275
17	5.75	97.00	0	0	0	0	28.38	1492.60	46.76	35	28.23	1539.14	-0.37640	1492.38	1000	0.23	-46.54	1257
18	5.75	97.25	0	0	0	1	28.41	1493.10	45.96	30	28.27	1539.06	-0.36680	-999.00	-999	-999.00	-999.00	994
19	5.75	97.50	0	0	0	1	28.46	1497.93	41.10	25	28.33	1539.03	-0.35642	-999.00	-999	-999.00	-999.00	499
20	5.75	97.75	0	0	1	1	28.51	1503.25	35.75	25	28.34	1539.00	-0.35909	-999.00	-999	-999.00	-999.00	196
21	5.75	98.00	0	0	1	1	28.54	1526.24	12.77	20	28.39	1539.01	-0.29423	-999.00	-999	-999.00	-999.00	105
22	5.75	98.25	0	0	1	1	28.56	1526.45	12.54	20	28.39	1538.99	-0.28776	-999.00	-999	-999.00	-999.00	102
23	5.75	98.50	0	0	1	1	28.59	1527.08	11.93	20	28.41	1539.02	-0.28276	-999.00	-999	-999.00	-999.00	101
24	5.75	98.75	0	0	1	1	28.63	1527.81	11.27	20	28.45	1539.07	-0.29056	-999.00	-999	-999.00	-999.00	100
25	5.75	99.00	0	0	1	1	28.69	1529.92	9.21	20	28.50	1539.13	-0.28272	-999.00	-999	-999.00	-999.00	99
26	5.75	99.25	0	0	1	1	28.75	1532.99	6.12	20	28.56	1539.11	-0.14813	-999.00	-999	-999.00	-999.00	87
27	5.75	99.50	0	0	0	1	28.80	1535.43	3.59	20	28.61	1539.02	-0.09014	-999.00	-999	-999.00	-999.00	68
28	5.75	99.75	0	0	0	1	28.84	1536.35	2.56	20	28.65	1538.90	-0.08897	-999.00	-999	-999.00	-999.00	57
29	5.75	100.00	1	0	0	1	28.86	1537.89	0.74	35	28.30	1538.63	0.01104	-999.00	-999	-999.00	-999.00	39
30	5.75	100.25	1	0	0	1	28.87	1538.75	0.03	20	28.63	1538.78	0.01330	-999.00	-999	-999.00	-999.00	23
31	5.75	102.50	1	1	0	1	27.28	1536.83	-0.07	4	27.29	1536.77	0.03299	-999.00	-999	-999.00	-999.00	5
32	5.75	102.75	1	1	0	1	27.27	1537.17	-0.23	20	27.27	1536.94	0.02461	-999.00	-999	-999.00	-999.00	23
33	5.75	103.00	1	0	0	0	27.24	1537.16	-0.15	40	27.15	1537.00	0.01824	-999.00	-999	-999.00	-999.00	40

Figure 12. Microsoft Excel worksheet after importing an SSP descriptor text (.txt) file.

2. Wind Speed and Wave Height

The SMGC database not only includes numerical values for mean wind speed, mean wave height, wind speed standard deviation, and wave height standard deviation but also a MATLAB-recognized parameter "NaN". The "NaN," defining "not a number," allows undefined numerical values to be carried with data having a numerical value. For the SMGC data, any point on land or missing data was assigned "NaN". The "NaN" term is not recognized by ArcMap and once the data was loaded into MATLAB, several lines of code were included in the program to assign "-999" to points having "NaN" values. A matrix was created containing values for latitude, longitude, and the four parameters and was saved in a text file. Twelve iterations of the program were run, once for each month, generating 12 text files of 65,341 points (rows) and 3.1 megabytes each.

The 12 text files were manipulated in Excel in a similar manner to the manipulation of the SSP files. However, because each file length was less than the maximum allowable length of one Excel spreadsheet (65,536), importation of one monthly file was completed at one time. Number formatting and saving as a dBase file were performed and the data was ready for importing into ArcMap.

3. Sediment Thickness

Sediment Thickness data, already in an ArcMap-recognizable shapefile (.shp), required no manipulation.

4. Sediment Type

The Surface Sediment Type database was already shapefile (.shp) formatted, and required no further manipulation.

E. IMPORT DATA INTO ARCMAP SOFTWARE

1. ArcMap

The ArcMap software used to perform analogous area determination and display is a highly capable software component of the latest ArcGIS Desktop software (ArcMap 9.2) by the Environmental Systems Research Institute (ESRI). The ArcGIS Desktop suite is a complete GIS software package that allows users to analyze spatial patterns, trends, and relationships that are not apparent in other software spreadsheets and databases. The software has the capability of displaying data on a map and allowing users to perform advanced geospatial analysis on the data and display the results (ESRI, 2008). ArcMap is the main application in ArcGIS used in mapping, editing, analysis, and querying. Geographic information is represented as a collection of layers that can either be displayed simultaneously or individually. The features of ArcMap make it ideal for use in analogous area determination.

2. Sound Speed Profile

Eleven individual dBase files for each month were created in the previous step of the process. The series of steps to import the files into ArcMap and prepare them for analogous area determination are: Importing and Appending, Displaying the Data, and Exporting the Data.

a. Importing and Appending

In order to start importing the dBase files into ArcMap it is necessary to create a new data frame upon opening the software. While only one data frame may be "active" at a time, each frame can contain as many layers as necessary. Importing the data into ArcMap is similar to importing data into Excel and can be performed by using the *Add Data* thumbnail on the toolbar. Only one of the 11 dBase files was added initially and, once imported, was assigned to the new data frame created. ArcMap has an *Append* feature that allows multiple data sets to be appended to the end of an existing data set if each contains equal number of columns. Figure 13 shows a snapshot of the *Append* feature when appending ten dBase files to a previously added file. To ensure all data was added to ArcMap during importation and appending, a cross-check with the Excel workbook was performed.

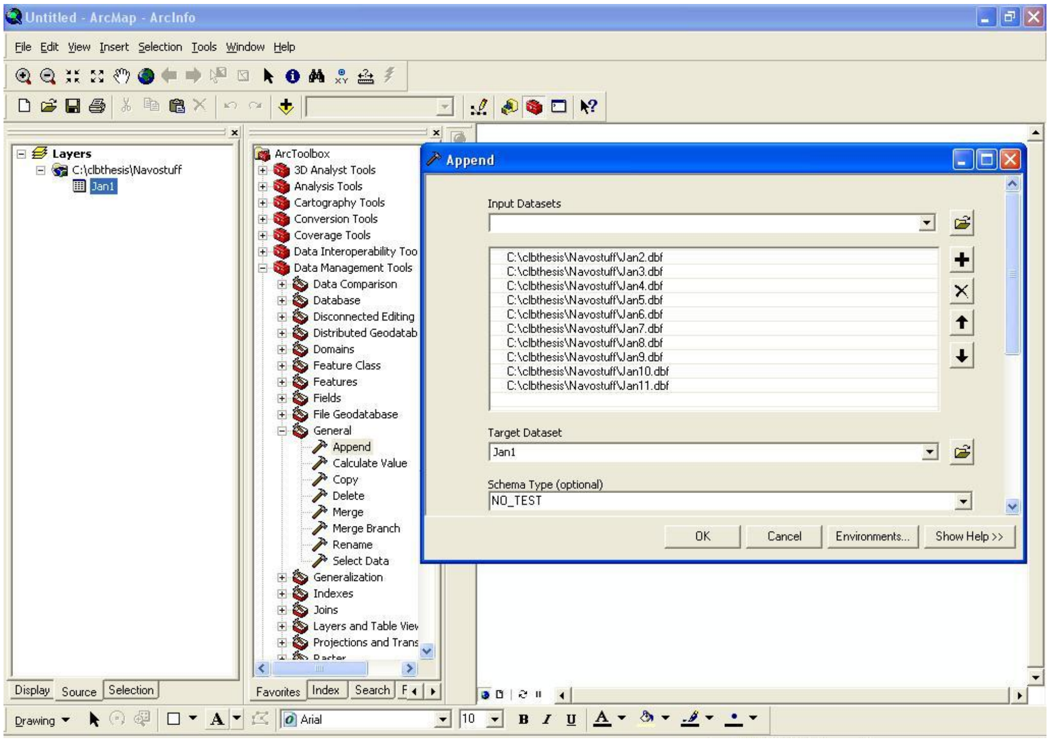


Figure 13. *Append* feature of ArcMap when importing January SSP .dbf files.

After importing and appending the 11 SSP descriptor dBase files, an attribute table is generated that, in appearance, is very similar to the Excel worksheet. When importing the first dBase file, the header information is maintained and during the appending process, the corresponding files of data are appended to the first file based on the header information. The attribute table generated when the importing and appending process are complete is shown in Figure 14. The attribute table will become very useful during performance of the analogous area query.

Attributes of January

FID	Shape *	LAT	LON	ISOV	UPG	DNG	NODSC	SURT	SVBOT	SVDIFF	MLD	MLT	MLSV	MAXG	DSCSV	DSCD	DSCST	SVEX	DEPTHMAX
0	Point	-78.5	-175.25	0	0	0	1	-0.73	1447.79	-3.39	300	-1.16	1444.4	-0.07239	-999	-999	-999	-999	578
1	Point	-78.5	-175	0	0	0	1	-0.73	1447.79	-3.39	300	-1.16	1444.39	-0.07333	-999	-999	-999	-999	578
2	Point	-78.5	-174.75	0	0	0	1	-0.74	1447.79	-3.39	300	-1.16	1444.39	-0.07427	-999	-999	-999	-999	564
3	Point	-78.5	-174.5	0	0	0	1	-0.74	1447.79	-3.39	300	-1.16	1444.4	-0.07426	-999	-999	-999	-999	564
4	Point	-78.5	-174.25	0	0	0	1	-0.73	1447.79	-3.38	300	-1.15	1444.42	-0.07639	-999	-999	-999	-999	546
5	Point	-78.5	-174	0	0	0	1	-0.72	1447.79	-3.35	300	-1.15	1444.44	-0.0773	-999	-999	-999	-999	546
6	Point	-78.5	-173.75	0	0	0	1	-0.72	1447.79	-3.34	300	-1.14	1444.46	-0.07728	-999	-999	-999	-999	525
7	Point	-78.5	-172.75	0	0	0	0	-0.64	1446.69	1.81	75	-0.85	1444.63	-0.08077	1442.83	75	1.81	2.06	479
8	Point	-78.5	-172.5	0	0	0	0	-0.63	1446.67	1.95	70	-0.81	1444.78	-0.08046	1442.83	75	1.95	1.89	479
9	Point	-78.5	-172.25	0	0	0	0	-0.62	1446.66	2.01	70	-0.8	1444.84	-0.0823	1442.83	80	2.01	1.82	478
10	Point	-78.5	-172	0	0	0	0	-0.6	1446.65	2.07	70	-0.78	1444.9	-0.08347	1442.83	80	2.07	1.75	484
11	Point	-78.5	-171.75	0	0	0	0	-0.59	1446.64	2.13	70	-0.77	1444.96	-0.0853	1442.83	80	2.13	1.68	484
12	Point	-78.5	-171.5	0	0	0	0	-0.57	1447.73	2.2	70	-0.76	1445.02	-0.08779	1442.82	80	2.2	2.71	500
13	Point	-78.5	-171.25	0	0	0	0	-0.55	1447.71	2.38	65	-0.71	1445.18	-0.09028	1442.8	80	2.38	2.53	500
14	Point	-78.5	-171	0	0	0	0	-0.54	1447.71	2.48	65	-0.7	1445.25	-0.0933	1442.78	80	2.48	2.46	528
15	Point	-78.5	-170.75	0	0	0	0	-0.52	1447.71	2.56	65	-0.68	1445.32	-0.09672	1442.76	80	2.56	2.39	528
16	Point	-78.5	-170.25	0	0	0	0	-0.46	1447.68	2.96	60	-0.6	1445.68	-0.10376	1442.72	90	2.96	2.01	575
17	Point	-78.5	-170	0	0	0	0	-0.45	1447.68	2.98	60	-0.59	1445.7	-0.10349	1442.72	90	2.98	1.97	575
18	Point	-78.5	-169.75	0	0	0	0	-0.44	1447.68	3	60	-0.59	1445.72	-0.10322	1442.72	90	3	1.96	587
19	Point	-78.5	-169.5	0	0	0	0	-0.44	1447.67	3.01	60	-0.59	1445.73	-0.10256	1442.73	90	3.01	1.94	592
20	Point	-78.5	-169.25	0	0	0	0	-0.43	1447.68	3.01	60	-0.58	1445.74	-0.10256	1442.73	90	3.01	1.93	592
21	Point	-78.5	-169	0	0	0	0	-0.43	1447.68	3.02	60	-0.58	1445.75	-0.10323	1442.73	90	3.02	1.93	593
22	Point	-78.5	-168.75	0	0	0	0	-0.42	1447.67	3.03	60	-0.58	1445.76	-0.10323	1442.73	90	3.03	1.91	593
23	Point	-78.5	-168.5	0	0	0	0	-0.42	1447.64	3.04	60	-0.58	1445.77	-0.10417	1442.73	90	3.04	1.87	591
24	Point	-78.5	-168.25	0	0	0	0	-0.41	1447.61	3.05	60	-0.57	1445.77	-0.10484	1442.72	90	3.05	1.83	569
25	Point	-78.5	-168	0	0	0	0	-0.41	1447.59	3.06	60	-0.57	1445.78	-0.10578	1442.71	90	3.06	1.81	569
26	Point	-78.5	-167.75	0	0	0	0	-0.4	1447.59	3.07	60	-0.57	1445.78	-0.10672	1442.71	90	3.07	1.81	569
27	Point	-78.5	-167.5	0	0	0	0	-0.4	1447.6	3.08	60	-0.57	1445.78	-0.10739	1442.7	90	3.08	1.82	547
28	Point	-78.5	-167.25	0	0	0	0	-0.39	1447.61	3.08	60	-0.57	1445.77	-0.10927	1442.69	90	3.08	1.84	528
29	Point	-78.5	-167	0	0	0	0	-0.39	1447.59	3.07	60	-0.58	1445.74	-0.10996	1442.68	90	3.07	1.85	528
30	Point	-78.5	-166.75	0	0	0	0	-0.4	1447.56	3.18	55	-0.55	1445.84	-0.11185	1442.67	90	3.18	1.71	516
31	Point	-78.5	-166.5	0	0	0	0	-0.4	1447.52	3.15	55	-0.55	1445.81	-0.11255	1442.66	90	3.15	1.72	516
32	Point	-78.5	-166	0	0	0	0	-0.43	1446.38	2.93	55	-0.6	1445.57	-0.11127	1442.64	90	2.93	0.81	489
33	Point	-78.5	-165.75	0	0	0	0	-0.45	1446.37	2.74	60	-0.65	1445.38	-0.10944	1442.64	90	2.74	0.99	489
34	Point	-78.5	-165.5	0	0	0	0	-0.46	1446.37	2.65	60	-0.67	1445.3	-0.10642	1442.65	90	2.65	1.07	475
35	Point	-78.5	-165.25	0	0	0	0	-0.48	1446.37	2.55	60	-0.68	1445.22	-0.10339	1442.67	90	2.55	1.15	475
36	Point	-78.5	-165	0	0	0	0	-0.5	1446.38	2.45	60	-0.7	1445.15	-0.09903	1442.7	90	2.45	1.22	483
37	Point	-78.5	-164.75	0	0	0	0	-0.52	1447.76	2.24	65	-0.74	1444.98	-0.09506	1442.74	90	2.24	2.78	510
38	Point	-78.5	-164.5	0	0	0	0	-0.53	1447.75	2.14	65	-0.76	1444.91	-0.09108	1442.77	90	2.14	2.83	510
39	Point	-78.5	-164.25	0	0	0	0	-0.55	1447.74	1.95	70	-0.8	1444.75	-0.08737	1442.8	90	1.95	2.99	507
40	Point	-78.25	179	0	0	0	1	-1.14	1451.38	-7.76	350	-1.35	1443.62	0.02776	-999	-999	-999	-999	744

Record: 1 Show: All Selected Records (0 out of 690642 Selected) Options

Figure 14. ArcMap Attribute Table for January SSP data.

b. Displaying the Data

To display geographic data, ArcMap requires that a specific coordinate system be selected as a grid reference for proper placement of values. The data is displayed in a 2-dimensional (2-D) Cartesian coordinate plane. Any header information similar to a geographic coordinate system (i.e. latitude/longitude) will automatically be the variables selected for the x and y-coordinates in the display option. Figure 15 shows the data display window and options for selecting coordinate variables. Notice that a geographic-coordinate system has been selected. After variables for the x and y coordinates are selected, ArcMap displays all parameters at their respective latitude and longitude locations.

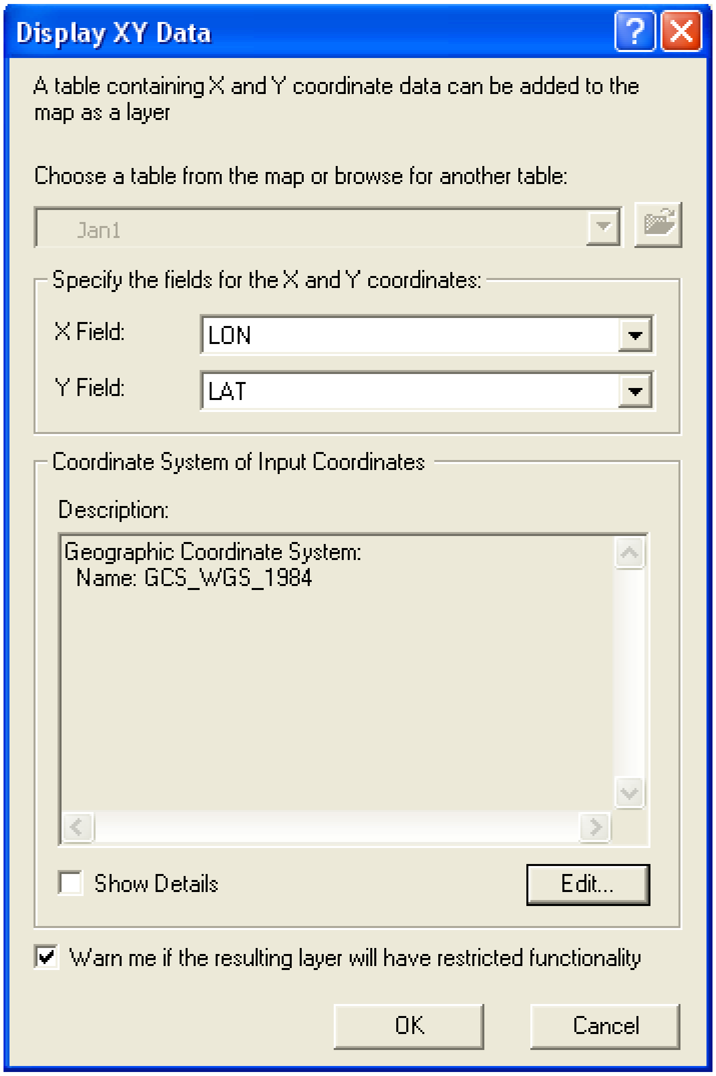


Figure 15. ArcMap Dialogue Box for displaying data.

ArcMap has the ability to individually display any SSP variable in the attribute table. This step can be performed after displaying the "xy" data. However, to understand the functionality of the display capability of ArcMap, it will be discussed here. The display box in Figure 16 shows the options for displaying variables. When displaying any one of the variables, it is important to ensure that the entire sample is included and that the points with no data (assigned a value of -999) are excluded.

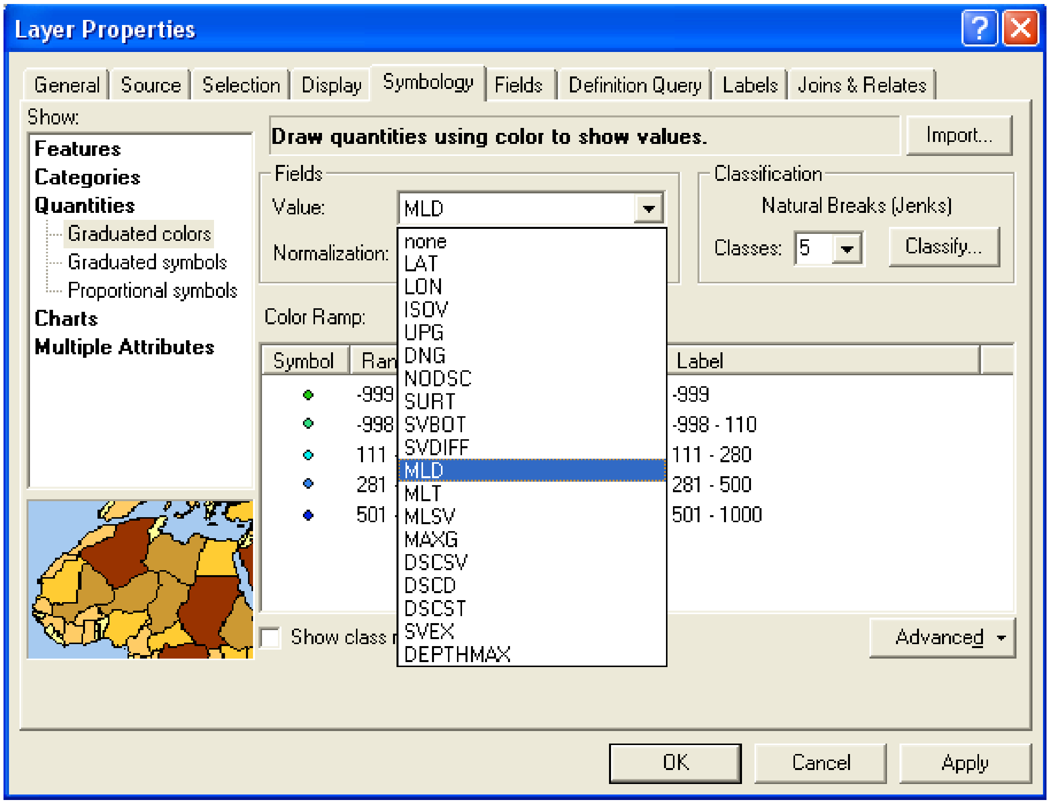


Figure 16. ArcMap Dialogue Box for displaying a single SSP descriptor.

Mixed Layer Depth (MLD) for January is shown in Figure 17. Cosmetic parameters like size, shape, and color can be adjusted to suit the needs of the user. The number of graduated categories can also be adjusted to meet the detail requirement of a user. In Figure 17, a 10-quantile criterion was selected for value graduation.

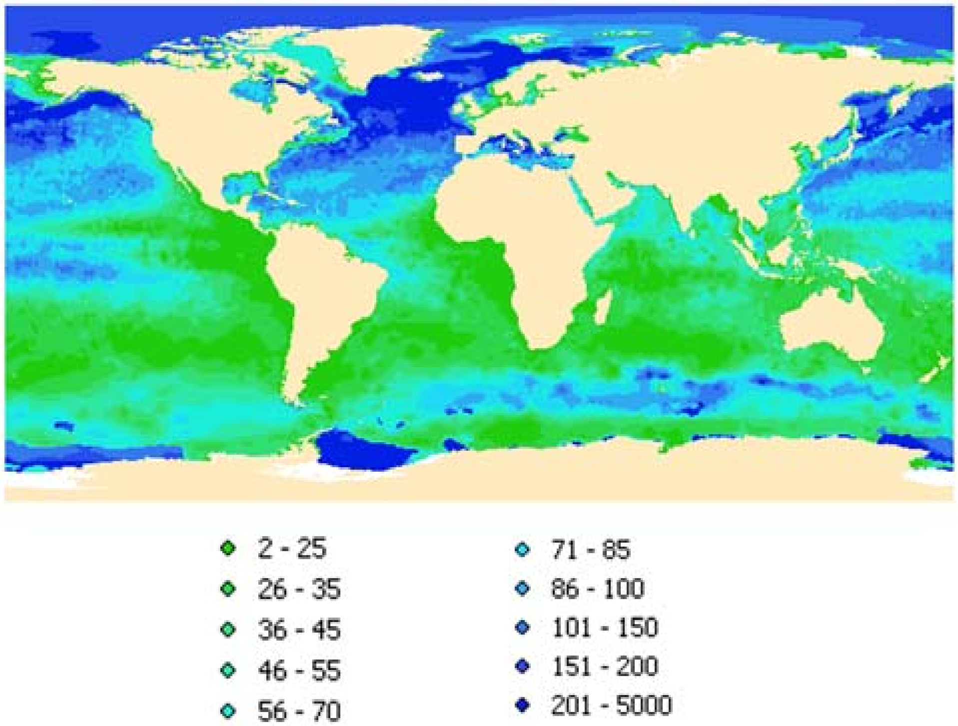


Figure 17. Mixed Layer Depth (MLD) for January. Units are in meters (m).

c. *Exporting the Data*

In the exporting process, the data imported into ArcMap as a dBase file is exported (saved) as a shapefile (.shp). After exporting the layer(s) in ArcMap, as shown in Figure 18, data can then be used for querying, the basis for analogous area search. During exporting, the data will be added as another layer within the active data frame and the original dBase layer can be removed.

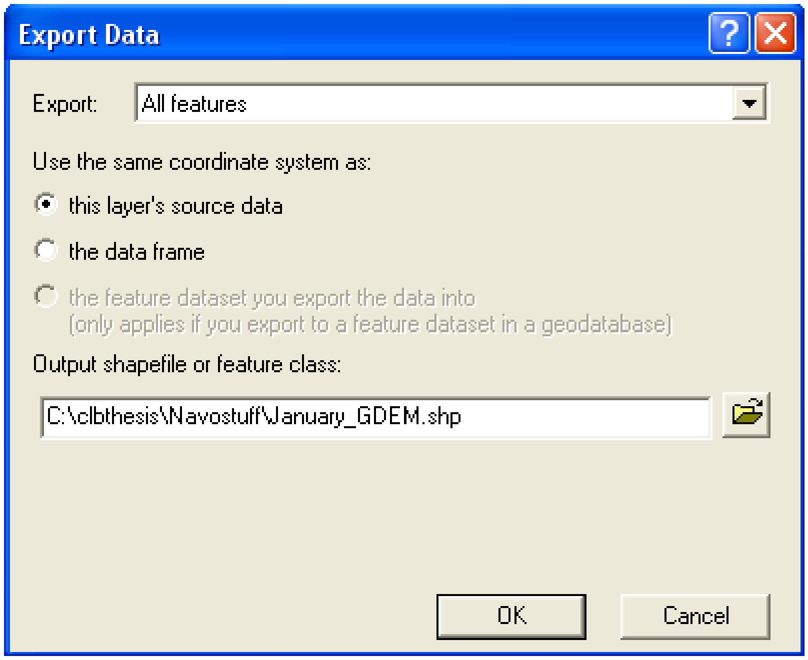


Figure 18. ArcMap Export Data dialogue box.

3. Wind Speed and Wave Height

The dBase files of wind speed and wave height data are imported into ArcMap similarly to the SSP data. Each file is for an entire month and does not require the appending process used for the SSP files. Data display and exportation processes are identical to the SSP. Figure 19 displays the mean wind speed for the month of January, binned into ten quantiles and symbolized with graduated color.

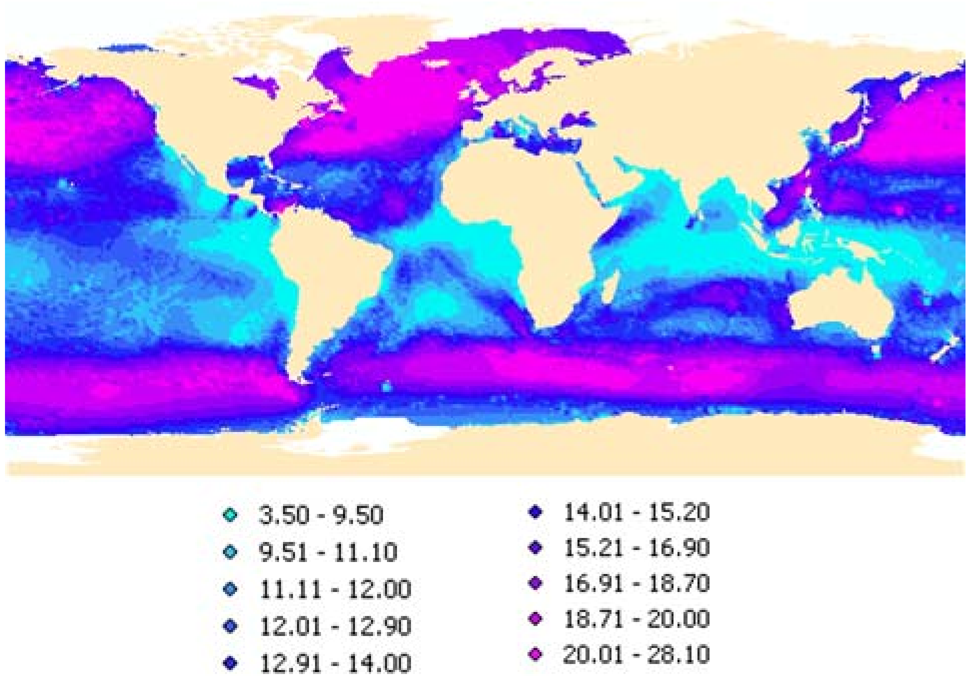


Figure 19. January Mean Wind Speed. Units are in meters/second (m/s).

4. Sediment Thickness

The sediment thickness file, already in a shapefile format, is imported into ArcMap. No further manipulation is required in ArcMap other than changing the display options, ensuring that all samples are included. The global sediment thickness is displayed in Figure 20. White areas are locations with no data.

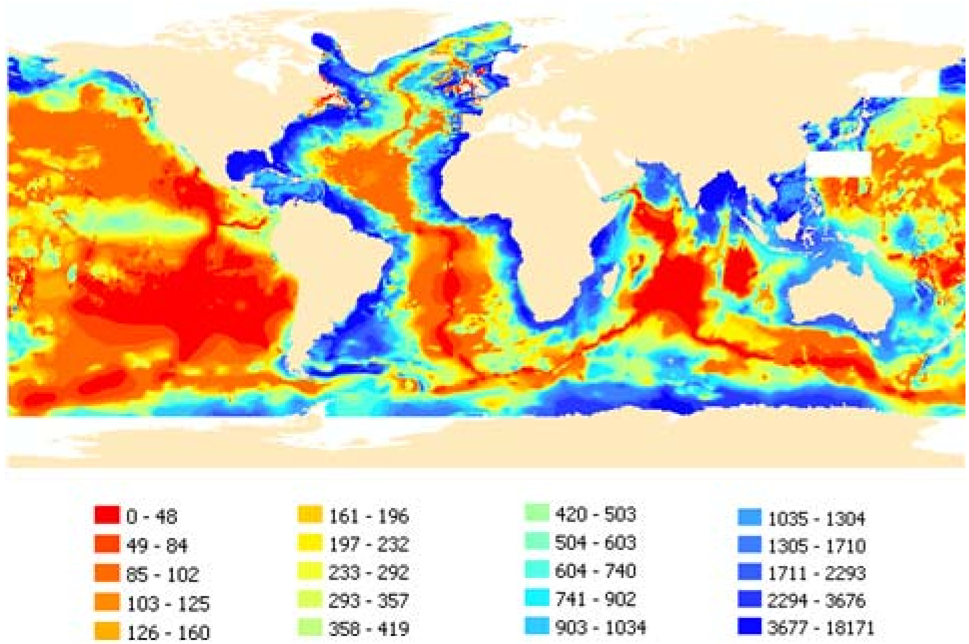


Figure 20. ArcMap display of global Sediment Thickness. Units are in meters (m).

5. Sediment Type

The Surface Sediment Type HFEVA data, also in shapefile format, required no additional manipulation to import into ArcMap. Loaded into the active layer with the *Add Data* feature, the layer needed manipulation only to change the display. Figure 21 is the HFEVA Surface Sediment Type ArcMap graphical display. Land and areas of no data are filled in with white.

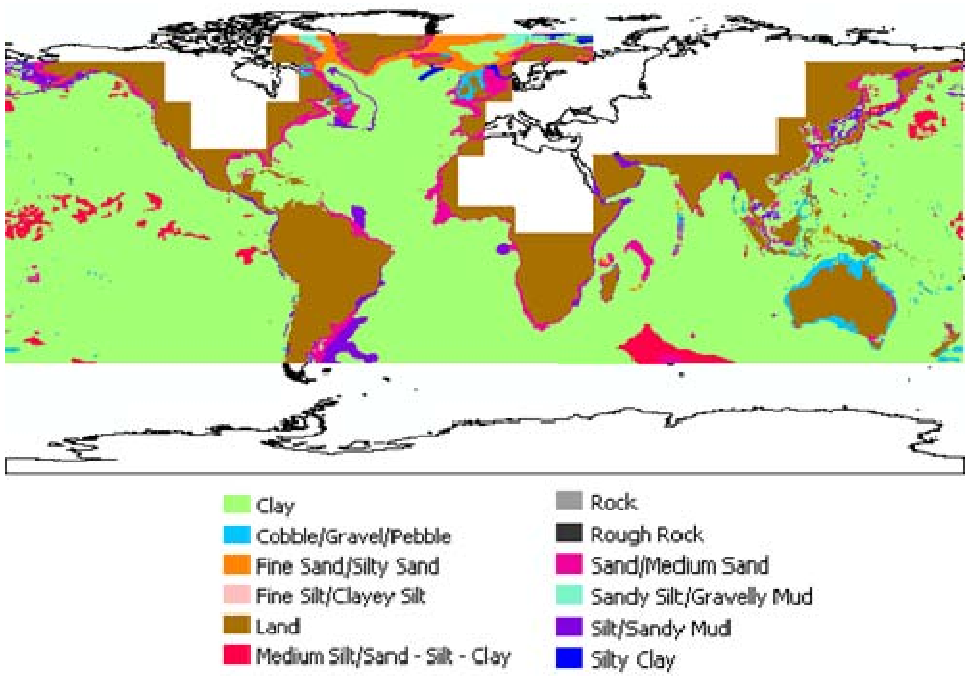


Figure 21. ArcMap display of HFEVA Surface Sediment Type

Twelve data frames were created, one for each month, and SSP descriptor data, wind speed and wave height data, sediment thickness, and sediment type for each month were added to the correct monthly data frame. After importation of all monthly data, analogous area determination could be performed. Figure 22 is a snapshot of the ArcMap display after all 12 monthly data frames were created and data added. Each data frame, at this point in the process, contained five layers: four for the imported data sets and one for the continents. The "active" data frame is in bold and only selected layers in that active data frame are displayed. The layers within a data frame are displayed in the order in which they are present in the data frame. In Figure 22, March is the active data frame and only Sediment Thickness, HFEVA Sediment Type, and continents are displayed, with Sediment Thickness displayed on top.

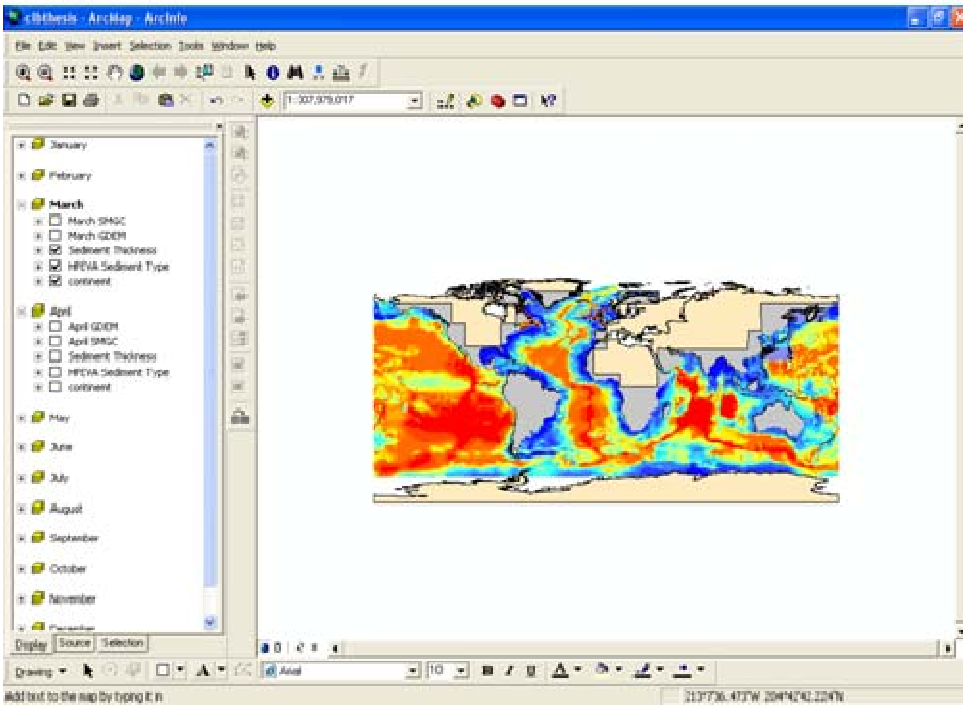


Figure 22. ArcMap Display after all 12 months of SSP descriptors, SMGC wind speed and wave height, and sediment type and thickness data have been added.

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IV. PERFORMING THE ANALOGOUS AREA SEARCH

At the heart of the analogous area search is ArcMap's ability to query data that has been added. ArcMap does not have the ability to query simultaneously between data frames or between layers in a data frame but other features exist that allow the analogous areas of one data layer to be the only locations that the query of the next layer can select from. Performing the analogous area search involves a small number of sub-steps and each will be discussed here. The general process consists of finding the locations that first meet the query criterion of one layers' descriptors and then using those areas to begin the selection of the next layer's descriptors. The selected analogous areas of one data set are used as the initial locations for the next search and so forth.

A. LOCATE TARGET AREA SSP DESCRIPTORS, WIND SPEED AND WAVE HEIGHT, SEDIMENT THICKNESS, AND SEDIMENT TYPE

1. SSP Descriptors

The first step in using ArcMap's querying capability is determining the target area's SSP descriptor values for the month in which an exercise or mission is to take place. From the attribute table, the latitude and longitude of the target area can be queried. The ArcMap attribute table returns the results of the search and are highlighted in the table. After locating the target area, the SSP descriptors were copied into an Excel spreadsheet for use in a later step. For the example used in this thesis, the mission in the target area is to be conducted in January. The dialogue box used for querying the target area's January SSP descriptors is displayed in Figure 23 with the results highlighted in Figure 24.

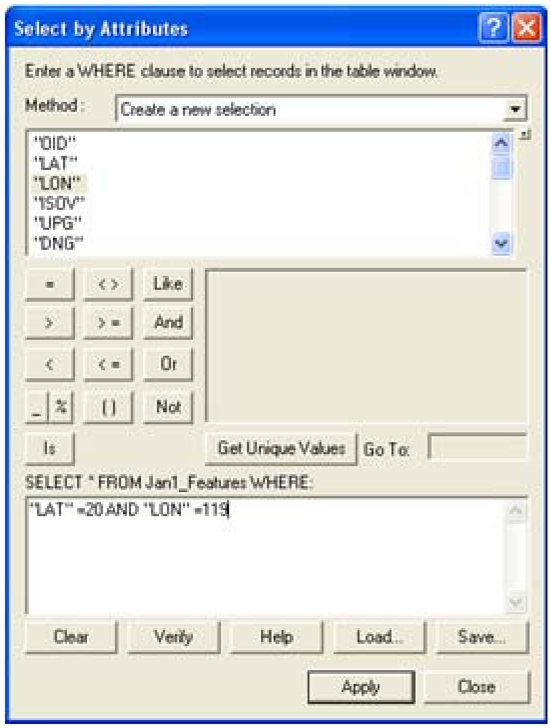
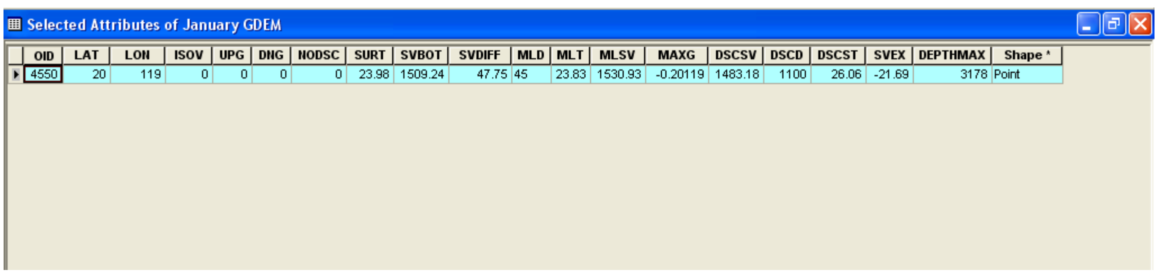


Figure 23. ArcMap Dialogue Box for querying target area SSP descriptors.



Selected Attributes of January GDEM

OID	LAT	LON	ISOV	UPG	DNG	NODSC	SURT	SVBOT	SVDIFF	MLD	MLT	MLSV	MAXG	DSCSV	DSCD	DSCST	SVEX	DEPTHMAX	Shape *
4550	20	119	0	0	0	0	23.98	1509.24	47.75	45	23.83	1530.93	-0.20119	1483.18	1100	26.06	-21.69	3178	Point

Figure 24. ArcMap result of query of target area parameters.

2. Wind Speed and Wave Height

The target area wind speed and wave height values are obtained in the same manner as obtaining the SSP descriptor values. Wind speed and wave height values are copied into an Excel worksheet for later use.

3. Sediment Thickness

Because the sediment thickness data is not displayed as a latitude and longitude point like the SSP and SMGC data, but rather as polygons, there is no ability to query for the target area sediment thickness according to latitude and longitude. ArcMap's *Identify* tool was used to determine the sediment thickness. Coordinates of the map cursor are displayed below the map and once the cursor is on the desired latitude and longitude, clicking on that point will return the value (see Figure 25). The values for sediment thickness are known as GRIDCODEs. The sediment thickness data is independent of the month so once the value has been determined for one month, the value can be used for successive months. The returned sediment thickness value of 2001 meters is then copied to an Excel worksheet for later use.

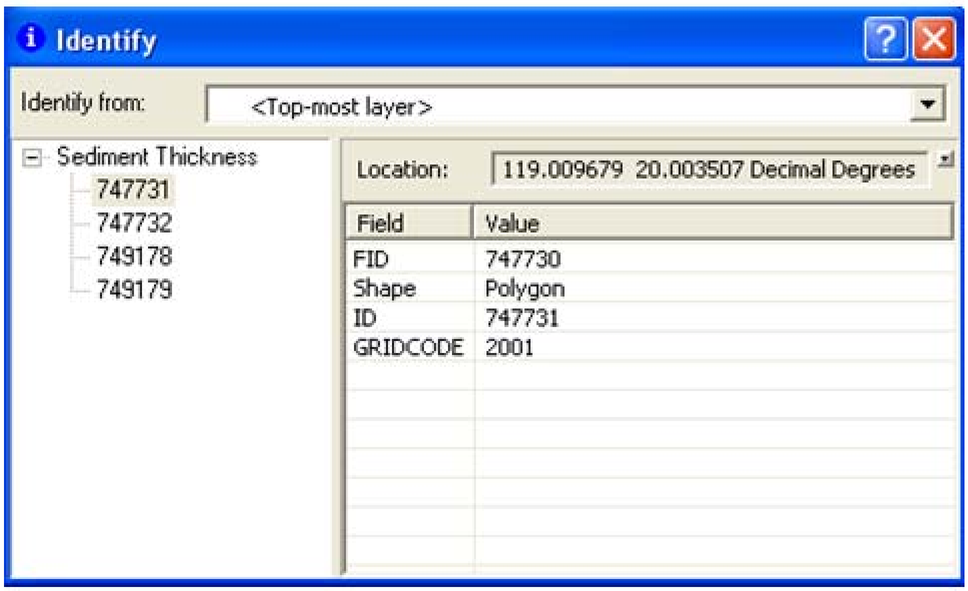


Figure 25. ArcMap's *Identify* tool for determining target area sediment thickness.

4. Sediment Type

The sediment type of the target area location is determined using the *Identify* tool as well. Here, as shown in Figure 26, sediment type is given in the LABEL field and for this target area example, is clay. Sediment type is also independent of the month and can therefore be used for any month during analogous area determination and is copied to an Excel worksheet with all of the other parameters' values.

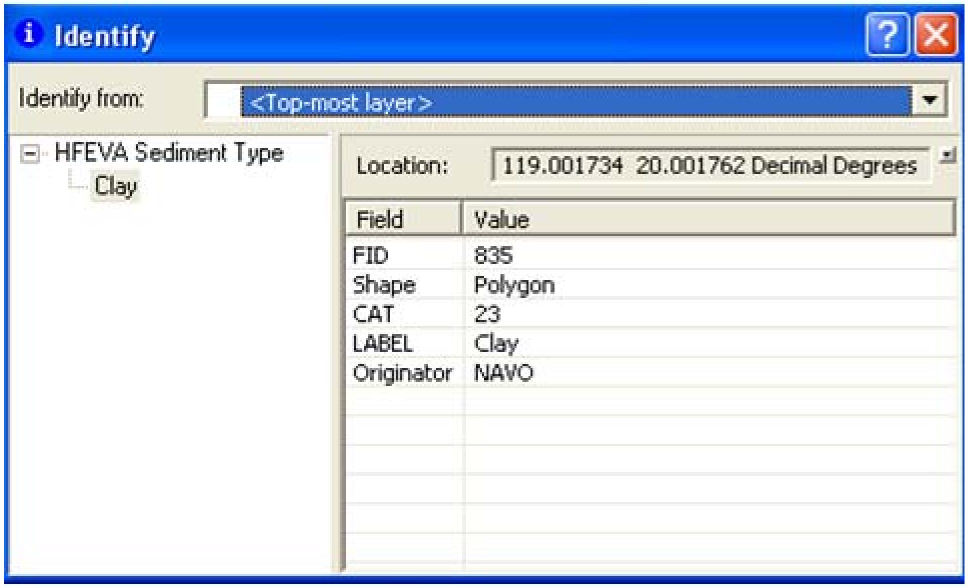


Figure 26. ArcMap’s *Identify* tool for determining target area sediment type.

When all values for the target area parameters have been identified and copied to an Excel spreadsheet, the important parameters for the specific mission are selected.

B. DETERMINE MISSION-IMPORTANT DESCRIPTORS

An ideal analogous area tool would have the capability to work for a variety of missions. The determination of the type of mission is of paramount importance because it affects the data used. Individual parameters (descriptors) within the data used to determine analogous areas for an ASW operation in deep water will be different from those chosen for use in a littoral mine-hunting scenario due to the contrast in environments. Not only does the mission type affect the selection of individual parameters but it also determines the importance (weight) of each parameter in the comparison process. The type of mission selected for this discussion is a deep-water ASW mission with the purpose of locating and tracking a submarine operating in the northeastern South China Sea.

There are a number of data sets that would benefit analogous area determination but the ones selected for use in this thesis provide significant acoustic relevance to identifying analogous areas. While wind speed and wave height data, sediment thickness, and sediment type are important for both deep water and shallow water missions, the importance of the individual SSP descriptors varies according to the mission and only the descriptors affecting sound propagation should be selected to determine analogous areas. The proper selection of SSP criteria has immense importance for the accuracy of the returned analogous areas.

1. Deep Ocean Important SSP Descriptors

The deep ocean sound propagation environment is profoundly different from the shallow water environment. Within the deep ocean, several layers can exist and long range sound propagation is possible. Many of the SSP descriptors defined are important in determining analogous areas for a deep-water mission. The most significant descriptors are: MLD, Thermocline Gradient, DSC Depth, DSC Sound Speed, DSC Strength, Sound Speed Excess, and Bottom Depth.

2. Shallow Water Important SSP Descriptors

Shallow water is defined as water less than 100 fathoms (~ 183 meters) in USW doctrine; it comprises approximately 7.6 percent of the world's oceans (NAVOCEANO, 1999, p. 93). Within this 7.6 percent, however, the acoustic environment is more variable and complex than in deeper waters. The biggest difference between shallow and deep waters is the lack of convergence zone propagation and a deep sound channel. The absence of both of these limits the range of acoustic propagation. The sound propagation in shallow waters is highly variable and depends on sea surface temperature (SST), salinity, MLD, water depth, and bottom composition. As sound propagates, the upper and lower boundaries of the shallow water environment (surface and bottom) form a channel of trapped sound. However, more transmission loss occurs per unit range in shallow water due to the multiple interactions with the surface and bottom. Environmental factors also have a more dramatic effect on the ambient noise in a shallow environment. Tides, upwelling, freshwater runoff, biologics, and shipping all affect the shallow-water acoustic propagation variability. In fact, shallow-water ambient noise levels are approximately 9 decibels (dB) higher than deep-water levels in the frequency range 100 Hz to 1 kHz for the same sea state and shipping density (NAVOCEANO, 1999, p. 95).

Selecting the SSP descriptors most important in shallow-water sound propagation is crucial in returning accurate analogous areas. These SSP descriptors are: SST (due to strong horizontal temperature variations over short distances), MLD and Mixed Layer properties (due to sudden variations in time and space), Bottom Depth, Bottom Sound Velocity (due to its affect on the acoustic impedance), and Sound Velocity Difference.

For the example presented here, the deep water ASW mission will use the deep-water SSP descriptors, wind speed, wave height, sediment thickness, and sediment type to determine the analogous areas for the target location.

C. WEIGHT THE PARAMETERS

The mission-dependent SSP parameters, wind speed, wave height, sediment type, and sediment thickness are important in finding analogous areas, but their relative importance is not equal. Therefore, it is necessary to apply a numerical "weight" to the various chosen parameters in order to account for their relative importance quantitatively. In the approach in "USW Area Analogs," weights were assigned to the fuzzy entropies calculated to achieve a "weighted match score" (Everett, 2005, p. 53-56). The weights could be adjusted in a MATLAB program according to mission type. Modification and re-running of computer programs every time a different mission is selected is very cumbersome and is avoided in the analogous area tool here.

Here, ArcMap is used to determine analogous areas by querying a range of values centered on the target area values. In order to apply the weighting in ArcMap, the range of the query is adjusted. For example, to find an exact match of the target area, a query of the exact values would be performed. While finding an area that is completely analogous to the target area would be ideal, the variability of the parameters prohibits such findings. However, if one parameter is more important than another, then limiting the range of the query for that parameter would apply a higher weight. This process was used when assigning weights here.

As a starting point, querying a range of values within 10 percent of the target area values could be performed. The resulting analogous areas would have parameter values that are within 10 percent of the target area values. If the results of the "10 percent criteria" yield no useful areas, then changing the query to values that are within 20 percent (30, 40, 50 percent, etc.) of the target area values, will likely yield more results. A process like this provides a scaled search and produces scaled results. In weighting the parameters, different percentage criteria of the target area's values are needed to be queried. For example, if DSC depth is more important than bottom depth, then querying for 10 percent around the target area's DSC depth and 20 percent around the target area's bottom depth would generate weighted results.

For the ASW example here, the "10 percent criteria" was used for DSC Depth, DSC Sound Speed, DSC Strength, MLD, Sound Speed Excess, and Thermocline Gradient. The "20 percent criteria" was used for Bottom Depth, Sediment Thickness, Sediment Type, Wind Speed, and Wave Height. To be complete, for a shallow water mission, querying criteria could be: "10 percent criteria" for MLD, MLT, Mixed Layer Sound Speed, Bottom Depth, Sediment Thickness, Sediment Type, Wind Speed, and Wave Height and "20 percent criteria" for Bottom Sound Speed, SST, and Sound Speed Difference. Technically, there is no scaled weighting for the Sediment Type parameter and all queries based on sediment type are exact-match queries. In addition, all binary SSP descriptors are used in the querying process so only SSPs whose binaries match exactly to the target area will be returned.

Two additional queries are used here to provide a comparison of the returned analogous areas after modification of the querying criteria: 1) "20 percent criteria" for MLD, Thermocline Gradient, DCS Sound Speed, DSC Depth, DSC Strength, and Sound Speed Excess and "30 percent criteria" for Bottom Depth, Wind Speed, Wave Height, and Sediment Thickness, and 2) "20 percent criteria for DSC Sound Speed, DSC Depth, DSC Strength, and Sound Speed Excess, "30 percent criteria" for MLD and Thermocline

Gradient, and "40 percent criteria" for Bottom Depth, Wind Speed, Wave Height, and Sediment Thickness. A summary of the query criteria and the associated parameters used in the ASW example analogous area search is in Table 4.

Query A	Query B	Query C
Exact Match Isovelocity Upward Refracting Downward Refracting No DSC Sediment Type **10 % criteria** DSC Sound Speed DSC Depth DSC Strength Sound Speed Excess MLD Thermocline Gradient **20% criteria** Bottom Depth Wind Speed Wave Height Sediment Thickness	**Exact Match** Isovelocity Upward Refracting Downward Refracting No DSC Sediment Type **20 % criteria** DSC Sound Speed DSC Depth DSC Strength Sound Speed Excess MLD Thermocline Gradient **30 % criteria** Bottom Depth Wind Speed Wave Height Sediment Thickness	**Exact Match** Isovelocity Upward Refracting Downward Refracting No DSC Sediment Type **20% criteria** DSC Sound Speed DSC Depth DSC Strength Sound Speed Excess **30% criteria** MLD Thermocline Gradient **40% criteria** Bottom Depth Wind Speed Wave Height Sediment Thickness

Table 4. Three query criteria used for analogous area determination.

The previously mentioned Excel spreadsheet containing the target area values have been modified to calculate the "10, 20, 30, and 40 percent criteria" query range values upon entering the target area's parameter values. This minimizes the amount of time needed to update query ranges if a change is needed or a new target area is selected. Because the user of the analogous area tool has full control over the query criteria, it is recommended that a sensitivity analysis be performed after all scenarios are run to find the most accurate weighting for the selected parameters.

D. DETERMINE THE ANALOGOUS AREAS

Once the mission-dependent parameters have been weighted and query ranges determined, ArcMap's ability to rapidly query a multitude of data points can be utilized. Since layers within the monthly data frames cannot be searched simultaneously, querying one data layer at a time is required. The order used to query here is Sediment Type, Sediment Thickness, SMGC Wind Speed and Wave Height, and SSP descriptors. The order was selected so that after all data layers have been queried, the resulting analogous areas could be identified by latitude and longitude within the attribute table. If sediment thickness or type were the final layer to be queried, locating the analogous areas by latitude and longitude would not be possible since these descriptors are not located in their attribute table. For the ASW example, the mission month is January so it is necessary to use the January target area values to query all months to find the analogous areas for each month. Mission planners can then decide which month provides the best opportunity to train.

1. Sediment Type

In the query process, ArcMap searches through the attribute table of data looking for locations that meet the criteria. The first step is to activate the January data frame, and from the "Selection" menu at the top of the screen, select the option "Select By Attributes". This option allows users to query data based on numerical values within the data layer. After selecting, another dialogue box will be displayed, as shown in Figure 27, in which the query criteria can be entered. Select the HFEVA Sediment Type data layer from which to search. Then, by clicking on the "CAT," which is the category of sediment, and formulating an equality statement as in Figure 27, the query can be performed. The target area sediment type is clay, whose "CAT" (category) is "23".

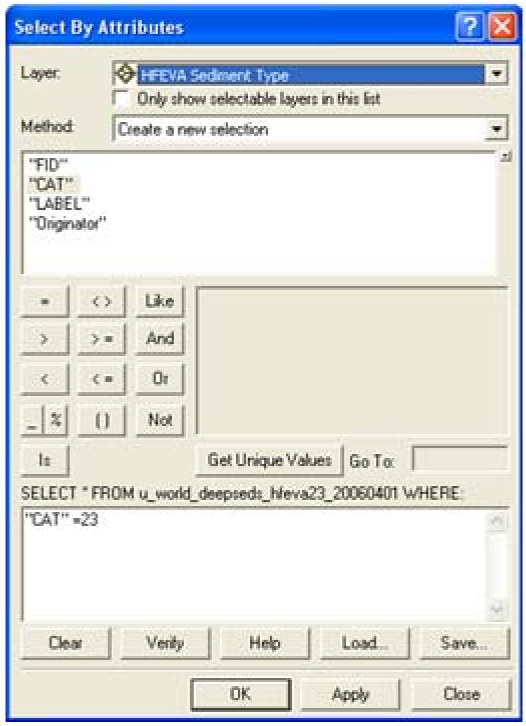


Figure 27. ArcMap dialogue box of "Select By Attributes" for HFEVA Sediment Type.

When the query is complete, any locations meeting the query criteria will be displayed on the map, as in Figure 28. Opening the attribute table for the HFEVA Sediment Type layer will also indicate how many records, if any, were found matching the criteria and clicking the "Show Selected" button will highlight the points meeting the entered criteria. The data is then exported to a new shapefile for use in the query of the next layer of data.

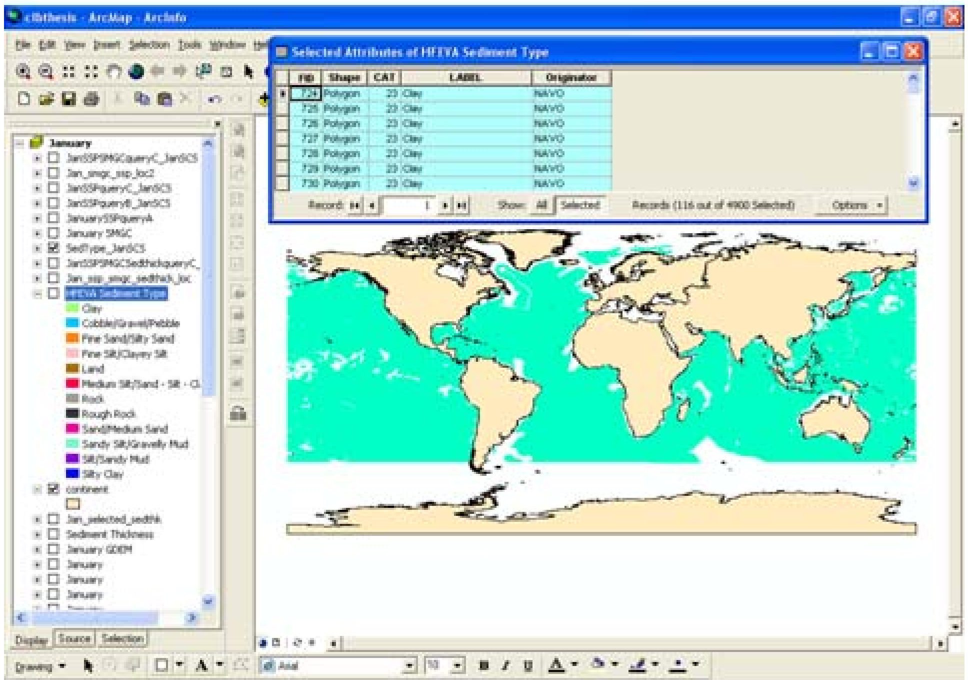


Figure 28. ArcMap display of HVEVA Sediment Type data meeting query criteria. Matching locations are displayed in green on the map and are highlighted in the attribute table.

2. Sediment Thickness

To include additional data not in the same layer as the HFEVA Sediment Type, the "Select By Location" feature is first used to select the data within the Sediment Thickness layer that matches the locations of the queried HFEVA Sediment Type data layer results. Figure 29 displays the dialogue box of performing the "Select By Location" to match the sediment thickness data to the area of the sediment type query result. It is important to "select features from" the layer that has not yet been queried and select the new exported queried layer as the one from which selection is performed. Areas of the sediment thickness layer that intersect the areas of the "clay" bottom type are selected and saved. However, sediment type does not have the extent of global coverage as sediment thickness and any sediment thickness areas outside the boundaries of the sediment type data will not be returned by the query. Having more sediment type coverage may be beneficial but any "cut off" locations that could have been analogous areas would be extremely far from USN homeports and most likely would not be used. The resulting "location match" of the sediment thickness data is then queried for sediment thickness values using the "Select By Attributes" feature as performed with sediment type. The query criterion is entered as an "AND" statement such as "Variable Name is greater than low end of query range AND Variable Name is less than high end of query range." The locations meeting the query criteria, if any, are displayed on the map and highlighted in the attribute table. The resultant layer is now useful for all months because the target area sediment thickness and sediment type do not temporally change and the layer can be copied into every other monthly data frame to continue the querying process.

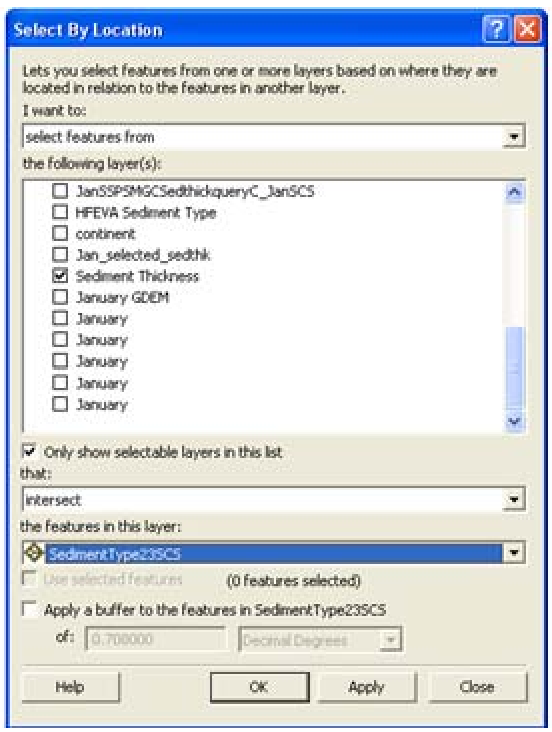


Figure 29. ArcMap dialogue box for matching sediment thickness layer to the queried result of the sediment type.

3. Wind Speed and Wave Height

To begin the query of wind speed and wave height, the “Select By Location” is performed as was completed on the Sediment Thickness data layer. The SMGC layer is selected to match the sediment type and sediment thickness analogous areas. The SMGC wind speed and wave height data are not at the same resolution as the sediment data (1° and .12°, respectively) and, therefore, the “intersect” option will not return the areas that match the queried sediment (type and thickness) data layer. In order to ensure that all queried sediment data are included in the “Select By Location” of the SMGC data, a buffer of .708 decimal degrees is created around the sediment data (see Figure 30) so any SMGC data point located within that distance will be returned. This value is slightly larger than the length of a line connecting the corner of a 1° by 1° box to the center of the box. The location-match result is then exported and queried using the “Select By Attributes” feature to identify analogous areas now meeting sediment type, sediment thickness, and wind speed and wave height criteria. The result is exported to a new layer.

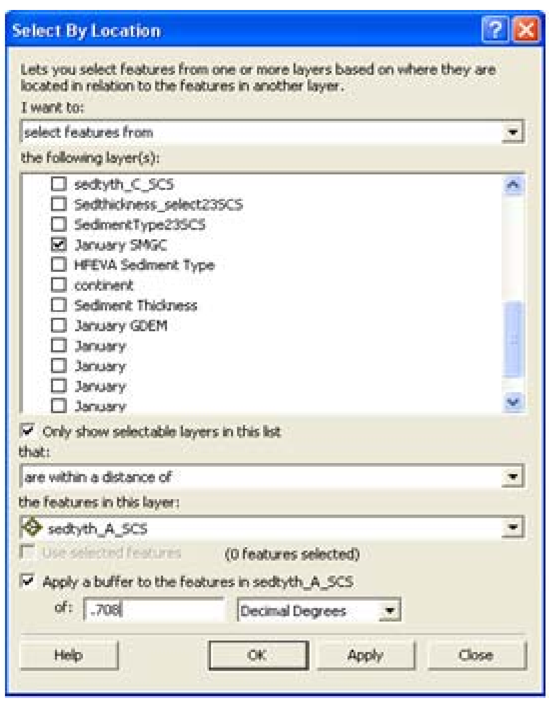


Figure 30. ArcMap dialogue box of matching SMGC data to sediment type and sediment thickness analogous areas.

4. SSP Descriptors

To complete the analogous area determination, the processes described in the previous sections are used to query within the SSP descriptors' data layer. The "Select By Location" feature, using the buffer of .708 decimal degrees as used in the previous section, is utilized first to reduce the SSP descriptor locations to match the analogous areas' layer produced from the Sediment Type, Sediment Thickness, and SMGC Wind Speed and Wave Height. A new layer, created after exporting the results of the "Search By Location" query, is then searched to locate the SSP descriptors matching the pre-determined selection criterion of section C. The analogous areas that are identified are the analogous areas that meet the criteria of all data used.

The process described in this section is reproduced for the 11 remaining months to determine the analogous areas for all months corresponding to the target area (for a particular month). From the monthly analogous areas, the best training options can be identified. The "best" options are determined by mission and exercise planners and depend on proximity to local homeports and time of year. Cosmetic procedures are used to generate a final display of the analogous areas.

E. DISPLAY THE ANALOGOUS AREA RESULTS

During the process described here, each new layer that is created during the exporting of the individual queries can be displayed by "checking" the box beside the layer name. While it is useful to observe the changes between the layers, the final display of the analogous area search result is the most useful and can be enhanced by adding additional shapefiles and changing the font options of the markers.

To display the analogous area maps here, two additional shapefiles are imported into ArcMap: one for displaying the ocean (in a light blue color) and one for displaying a grid of latitude and longitude lines at five degree intervals as shown in Figure 31. These shapefiles are optional but the aesthetics they provide in displaying the analogous area tool are beneficial.

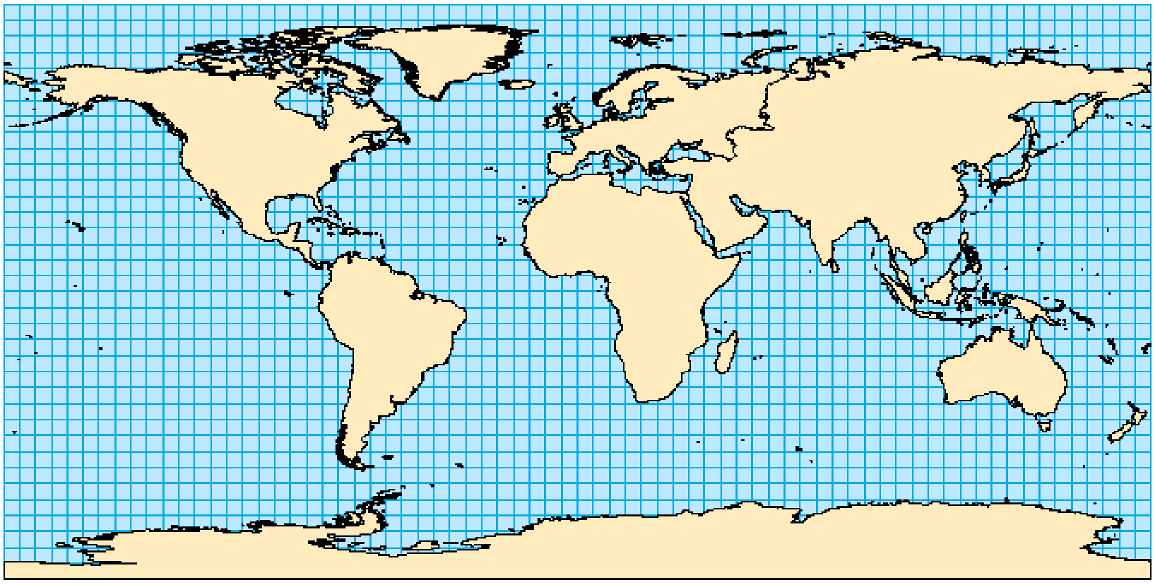


Figure 31. ArcMap display of continents, ocean color, and gridded latitude and longitude lines used for final display of analogous areas.

Results and validation of the analogous area search for the ASW mission example are presented in the next chapter.

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V. EXAMPLE ANALOGOUS AREA RESULTS

The steps provided in the previous chapter were used in determining the analogous areas, if any, for the ASW example presented here. The goal of the analogous area tool was to find locations that were environmentally similar to the target area during the month of January. Table 5 provides a summary of the target area's values for the SSP descriptors, SMGC wind speed and wave height, sediment type, and sediment thickness. Query criteria were applied to these values to determine the query parameters and ranges to be used in ArcMap. The results for Query A, Query B, and Query C follow.

PARAMETERS	Target Values
Latitude	20
Longitude	119
Isovelocity	0
Upward Refracting	0
Downward Refracting	0
No DCS	0
SST	23.98
Sound Speed @ bottom	1509.24
Sound Speed Difference	47.75
MLD	45
MLT	23.85
Mixed Layer Sound Speed	1530.93
Thermocline gradient	-0.20119
DSC Sound Speed	1483.18
DSC Depth	1100
DSC Strength	26.06
Sound Speed Excess	-21.69
Bottom Depth	3178
Mean Wind Speed	18.3
Mean Wave Height	1.9
Sediment Thickness	2001
Sediment Type	clay

Table 5. Summary of January Target Area parameters and values.

A. QUERY A

To test the analogous area tool, it was important to modify the weights of the parameters to observe a change in the analogous areas returned by the query. The set of criteria from Table 4 was used as a starting point to test the analogous area tool and was a combination of the “10 percent” and “20 percent” criteria. More important parameters to the ASW mission were assigned to the “10 percent” group and less important ones were assigned to the “20 percent” group. In this case, all analogous areas returned would have values within ten or twenty percent of the corresponding target area values.

1. ArcMap Display of Analogous Areas for Query A

After completing the process for Query A in ArcMap, the analogous areas were displayed as described in the previous chapter. Figures 32-34 are the monthly analogous areas corresponding to the target area in January. There were no returned analogous areas for April through December and only the displays of January, February, and March are provided. The analogous areas are displayed in magenta.

The displays of the analogous areas for these months are somewhat misleading in that the actual “area” shown in magenta is larger than the actual “point” where the analogous area is located. ArcMap automatically resizes the symbols based upon the scale of the display to allow easy identification of highlighted areas. Closer inspection of the areas in a larger scale display provides a more spatially accurate representation. As observed in Figures 32-34, the analogous areas for Query A are limited.

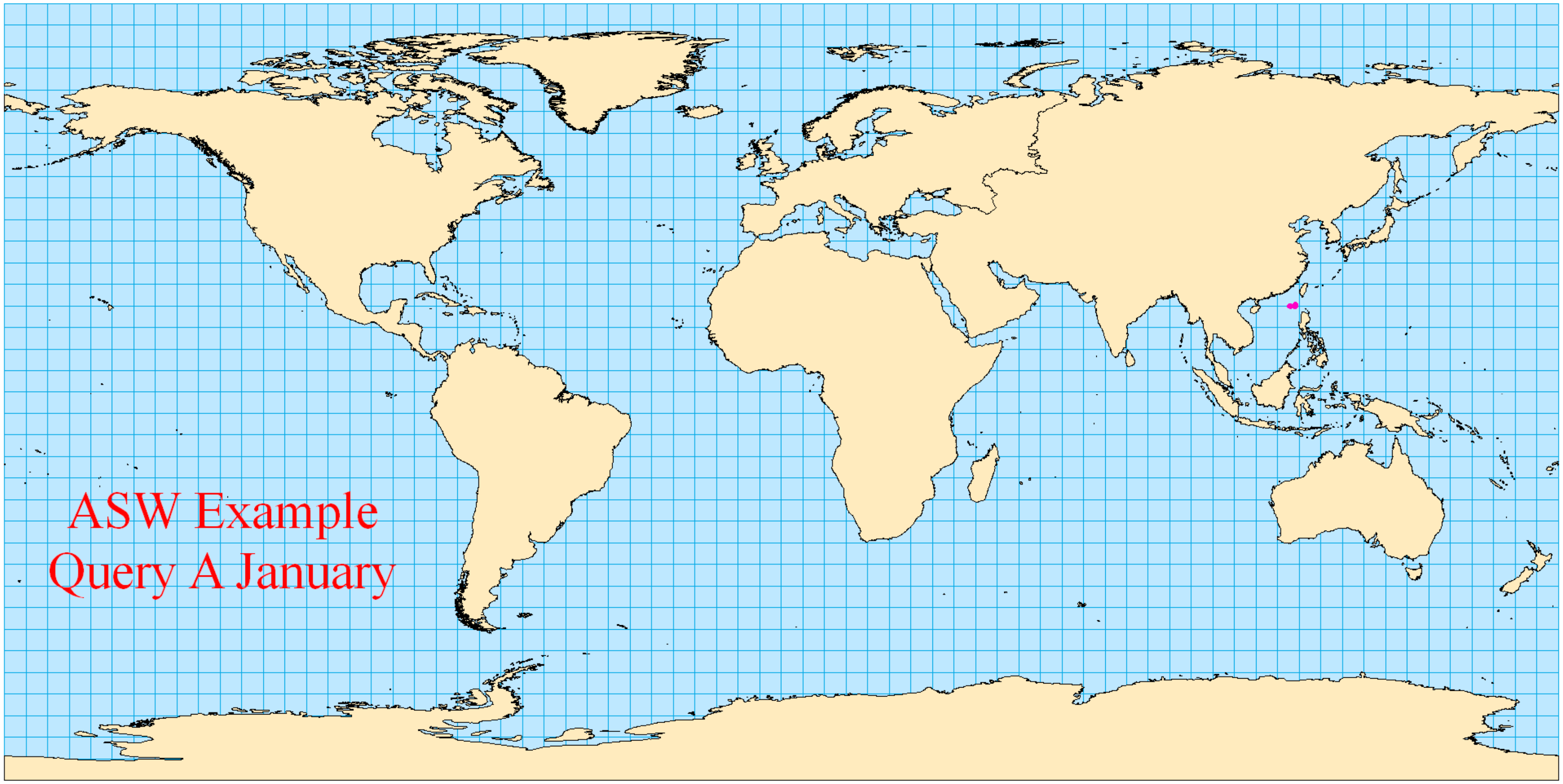

Figure 32. Query A analogous areas in January for Target Area in January.

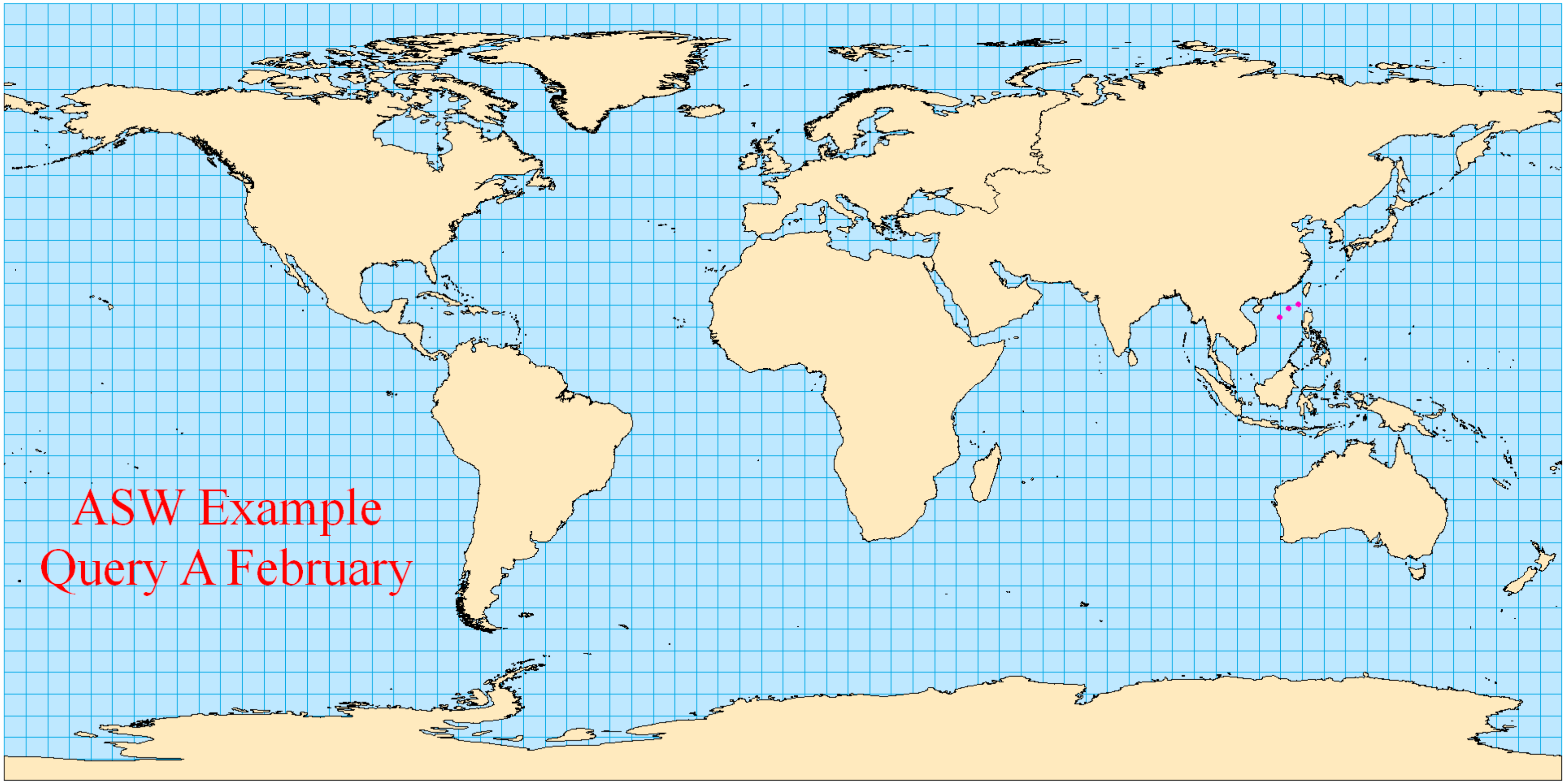

Figure 33. Query A analogous areas in February for Target Area in January.

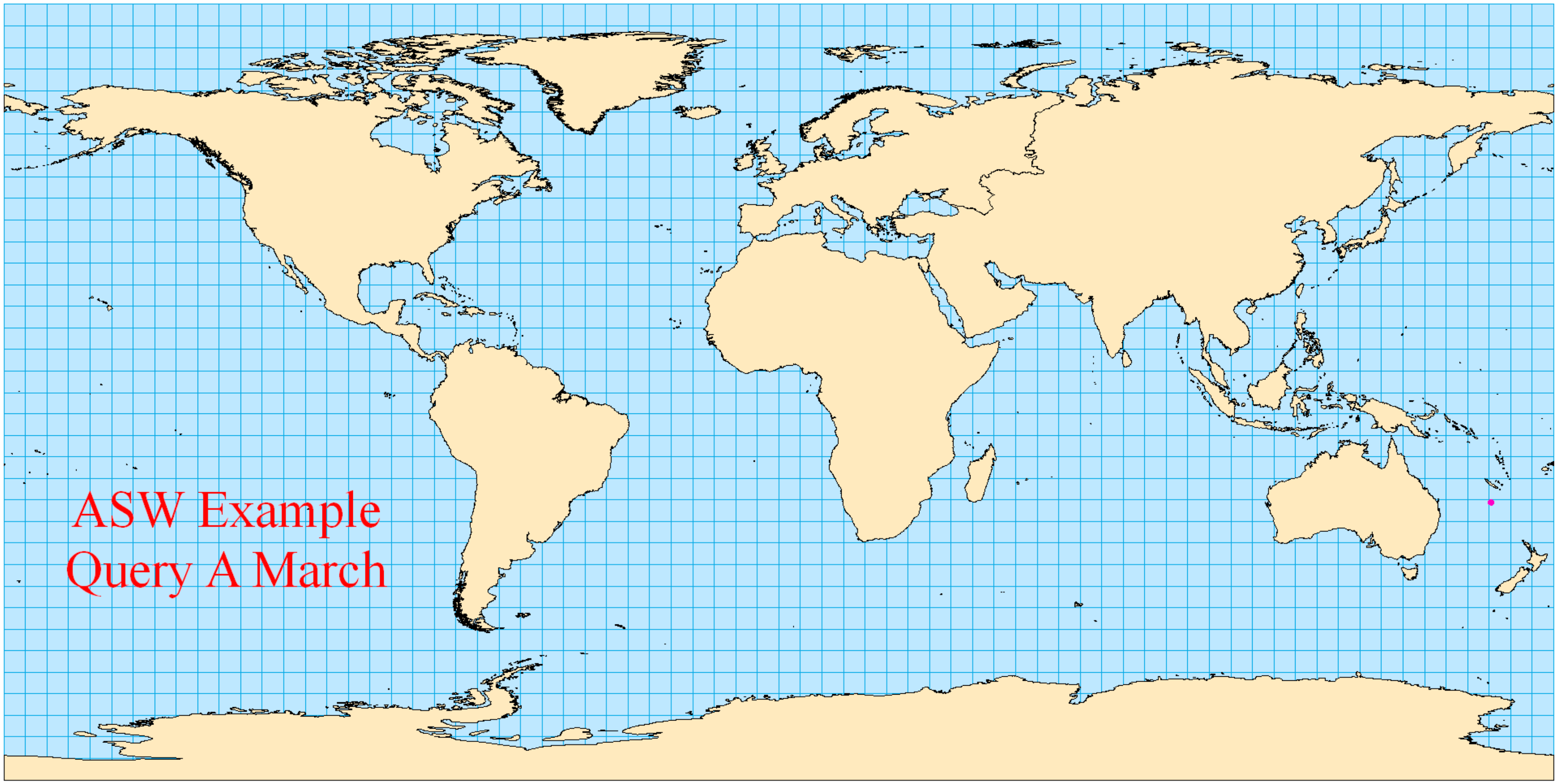

Figure 34. Query A analogous areas in March for Target Area in January.

The ArcMap attribute tables (Tables 6 through 8) display the actual latitude and longitude of the analogous areas as well as the value of their parameters. A quick spot-check of any location can be used to verify the queried parameter values meet the criteria of Query A. In Table 6, the actual target area (20°N, 119°E) is returned as an analogous area. Because query ranges were centered on the target area values for January, the return of the target area is expected and is the first verification that the analogous area tool is working correctly.

Attributes of Jan_qryAresult_JanSCS

FID	Shape *	LAT	LON	ISOV	UPG	DNG	NODSC	SURT	SVBOT	SVDIFF	MLD	MLT	MLSV	MAXG	DSCSV	DSCD	DSCST	SVEX	DEPTHMAX
0	Point	20	117.75	0	0	0	0	23.88	1509.29	47.44	45	23.72	1530.68	-0.18192	1483.24	1100	26.05	-21.38	3063
1	Point	20	118	0	0	0	0	24.03	1509.29	47.71	45	23.85	1530.98	-0.19204	1483.26	1100	26.03	-21.69	3174
2	Point	20	118.75	0	0	0	0	24	1509.24	47.74	45	23.85	1530.95	-0.19158	1483.22	1100	26.02	-21.71	3182
3	Point	20	119	0	0	0	0	23.98	1509.24	47.75	45	23.83	1530.93	-0.20119	1483.18	1100	26.06	-21.69	3178
4	Point	20.25	119	0	0	0	0	23.97	1509.24	47.91	45	23.85	1530.98	-0.18355	1483.07	1100	26.17	-21.74	3028

Record: 1 Show: All Selected Records (0 out of 5 Selected) Options

Table 6. Query A attribute table of January analogous areas with SSP descriptors.

Attributes of Feb_qryAresult_JanSCS

FID	Shape *	LAT	LON	ISOV	UPG	DNG	NODSC	SURT	SVBOT	SVDIFF	MLD	MLT	MLSV	MAXG	DSCSV	DSCD	DSCST	SVEX	DEPTHMAX
0	Point	17.25	114.75	0	0	0	0	24.62	1509.27	48.83	45	24.38	1532.02	-0.21586	1483.18	1000	26.09	-22.74	3119
1	Point	19.25	116.75	0	0	0	0	24.04	1509.24	48	45	23.87	1530.97	-0.21915	1482.97	1000	26.28	-21.73	3186
2	Point	20.25	119	0	0	0	0	23.96	1509.24	47.85	45	23.81	1530.9	-0.18145	1483.04	1100	26.2	-21.65	3028

Record: 1 Show: All Selected Records (0 out of 3 Selected) Options

Table 7. Query A attribute table of February analogous areas with SSP descriptors.

Attributes of Mar_qryAresult_JanSCS

FID	Shape *	LAT	LON	ISOV	UPG	DNG	NODSC	SURT	SVBOT	SVDIFF	MLD	MLT	MLSV	MAXG	DSCSV	DSCD	DSCST	SVEX	DEPTHMAX
0	Point	-25.75	165.25	0	0	0	0	25.27	1514.39	49.69	45	25.21	1535.81	-0.21178	1486.12	1200	28.27	-21.42	3413
1	Point	-25.75	165.5	0	0	0	0	25.18	1514.39	49.47	45	25.13	1535.61	-0.20297	1486.15	1200	28.24	-21.22	3495
2	Point	-25.5	165.25	0	0	0	0	25.29	1514.39	49.9	45	25.22	1535.86	-0.20895	1485.96	1200	28.42	-21.47	3554
3	Point	-25.5	165.5	0	0	0	0	25.22	1514.39	49.72	45	25.17	1535.71	-0.19646	1485.99	1200	28.4	-21.33	3595

Record: 1 Show: All Selected Records (0 out of 4 Selected) Options

Table 8. Query A attribute table of March analogous areas with SSP descriptors.

2. Visual Comparison of Sound Speed Profiles and Ray Traces

The sound speed profile (SSP) is, more than any other data set used here, the primary environmental characterization influencing acoustic sound propagation. Therefore, visual comparison of the target area SSP to the analogous area SSP validates the results of the process. The SSP for an analogous area in March, located at 25.75°S, 165.25°E, is used as an example for comparison with the January target area SSP and is shown in Figure 35. As can be observed, the two SSPs are very similar in shape with key features at almost identical depths; it is reasonable to expect the acoustic propagation characteristics in both environments would be similar.

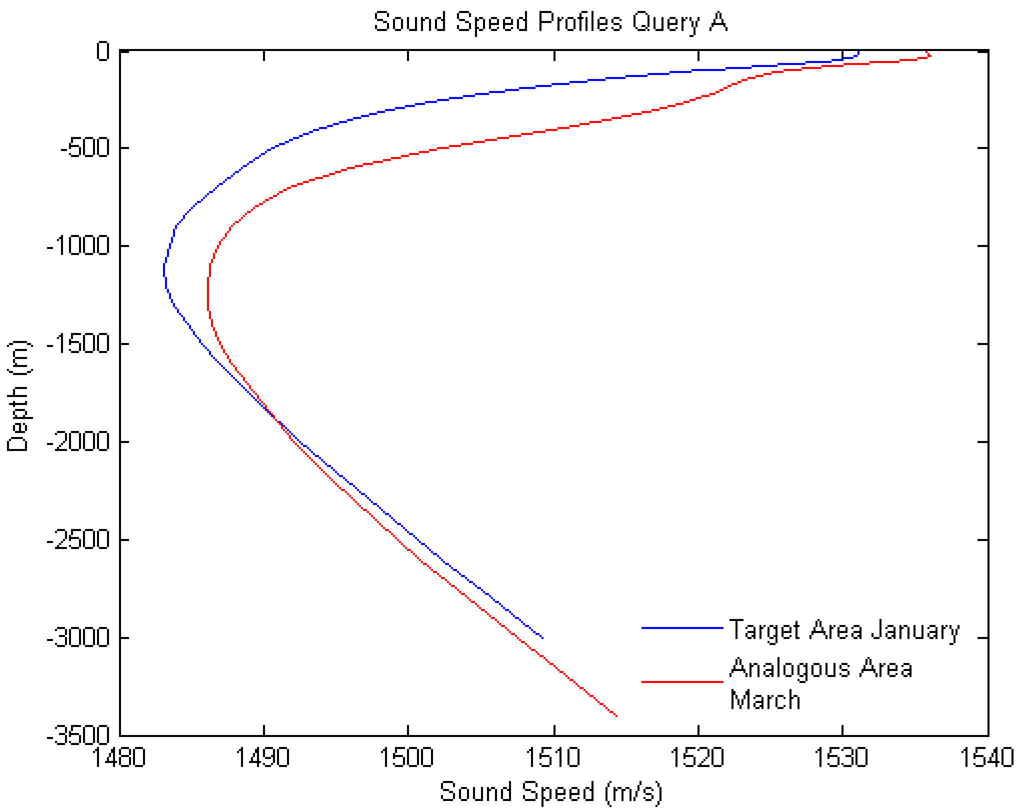

Figure 35. Sound Speed Profiles for Target Area in January (blue) and March analogous area (red) for Query A.

The ray traces (see Figures 36 and 37) for the target area in January and the March analogous area reveal the expected path sound rays would take based on the SSP structure. The rays shown are depictions of sound rays from a source at 100 meters launched at 21 different degree angles (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10), with the surface and bottom boundaries modeled as perfectly reflecting planar interfaces. The two ray trace plots are visually similar and, like the SSP comparison from above, validate the accuracy of the analogous area tool here.

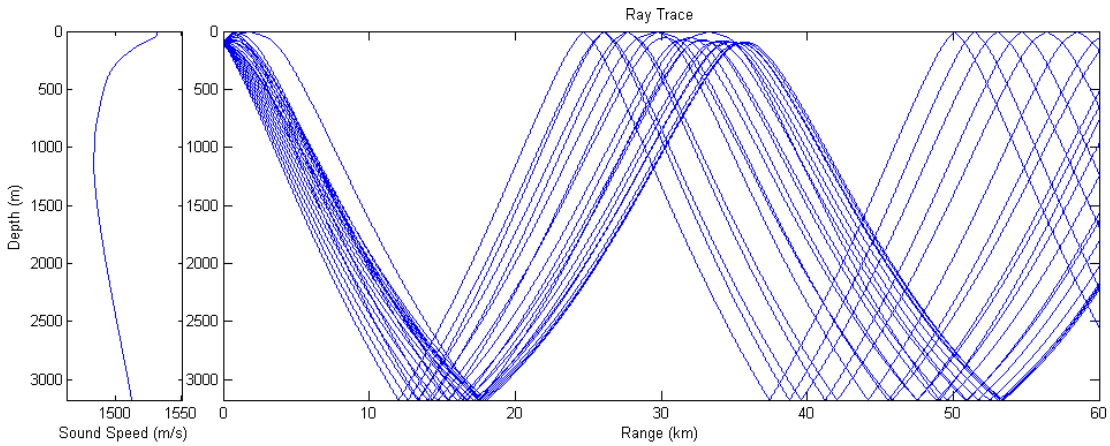

Figure 36. Query A ray trace of Target Area in January.

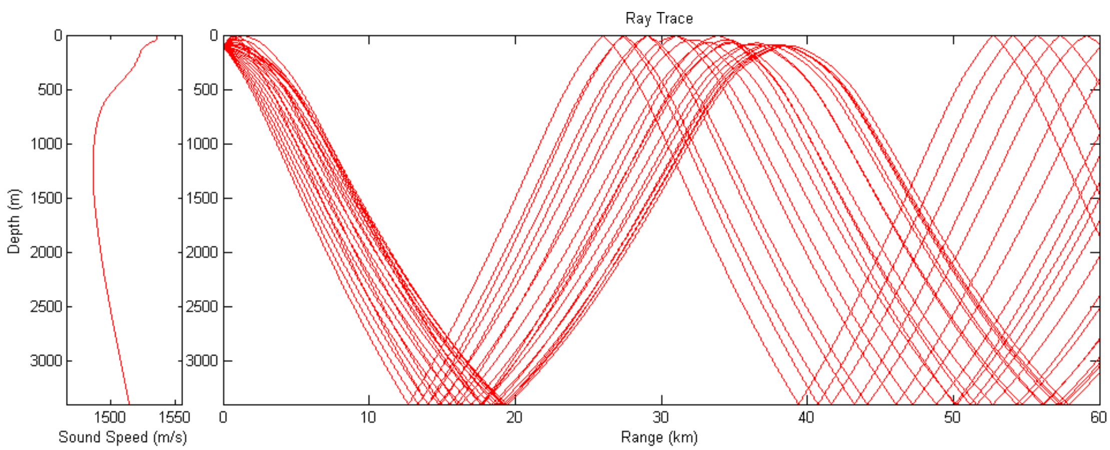

Figure 37. Query A ray trace of March analogous area.

B. QUERY B

Only 12 analogous areas were returned for the target area in January using Query A which are not useful for USN mission and exercise planners. None of the returned analogous areas are within close proximity to homeports. It will be up to the analogous area tool users to decide how much similarity can be sacrificed to find analogous areas close to USN waters and homeports. Query B criteria uses a wider range for the query as the important parameters are weighted differently from the criteria of Query A. Although

Query B is a less stringent query, the analogous areas returned have parameter values that are within 20 percent or 30 percent of the target area's January parameter values.

1. ArcMap Display of Analogous Areas for Query B

Figures 38-49 display the analogous areas found in each month according to Query B. Unlike the results of Query A, Query B produced analogous areas for all months. As before, the analogous areas are shown in magenta and can be highlighted in the attribute table to see the exact locations. The number of analogous areas per month produced for Query B is: January – 94, February – 134, March – 168, April – 88, May – 22, June – 27, July – 27, August – 10, September – 5, October – 21, November – 14, and December – 64. Based on numbers alone, it would appear that March provides the best option for training for the ASW mission, but closer inspection finds that the month providing options close to US homeports is October. Several analogous areas located in this month are off the east coast of the United States and in close proximity to U.S. homeports.

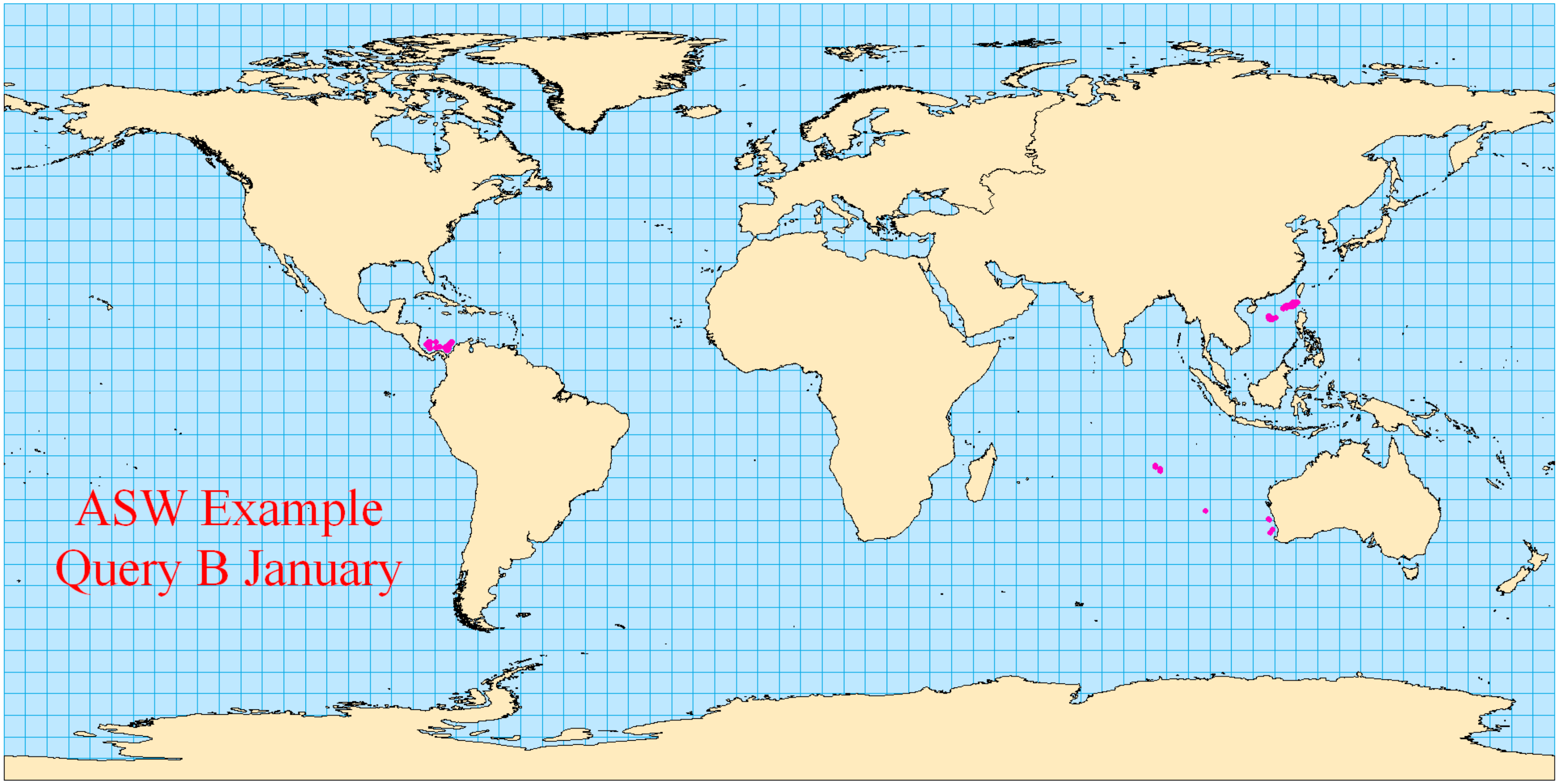

Figure 38. Query B analogous areas in January for Target Area in January.

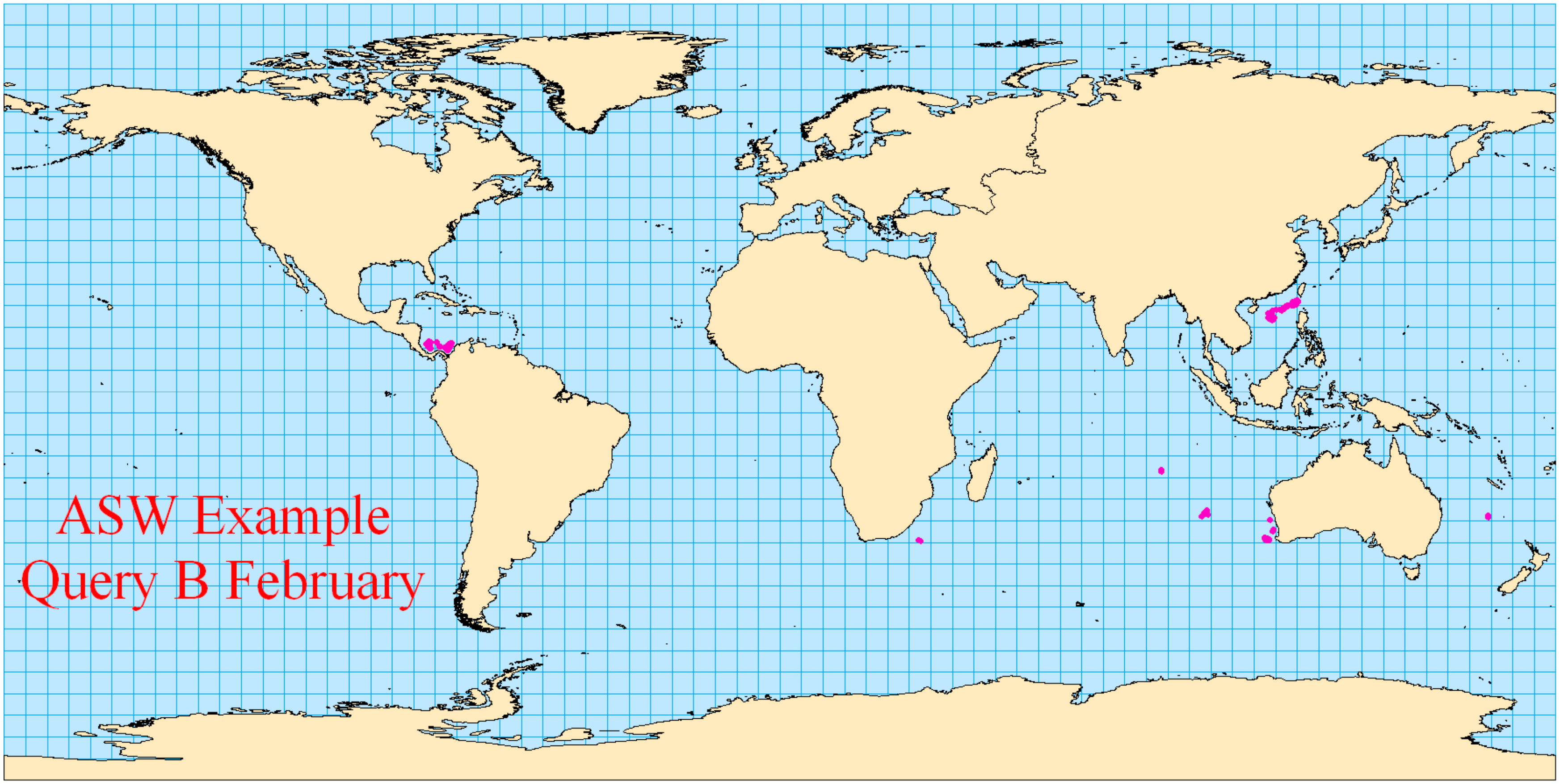

Figure 39. Query B analogous areas in February for Target Area in January.

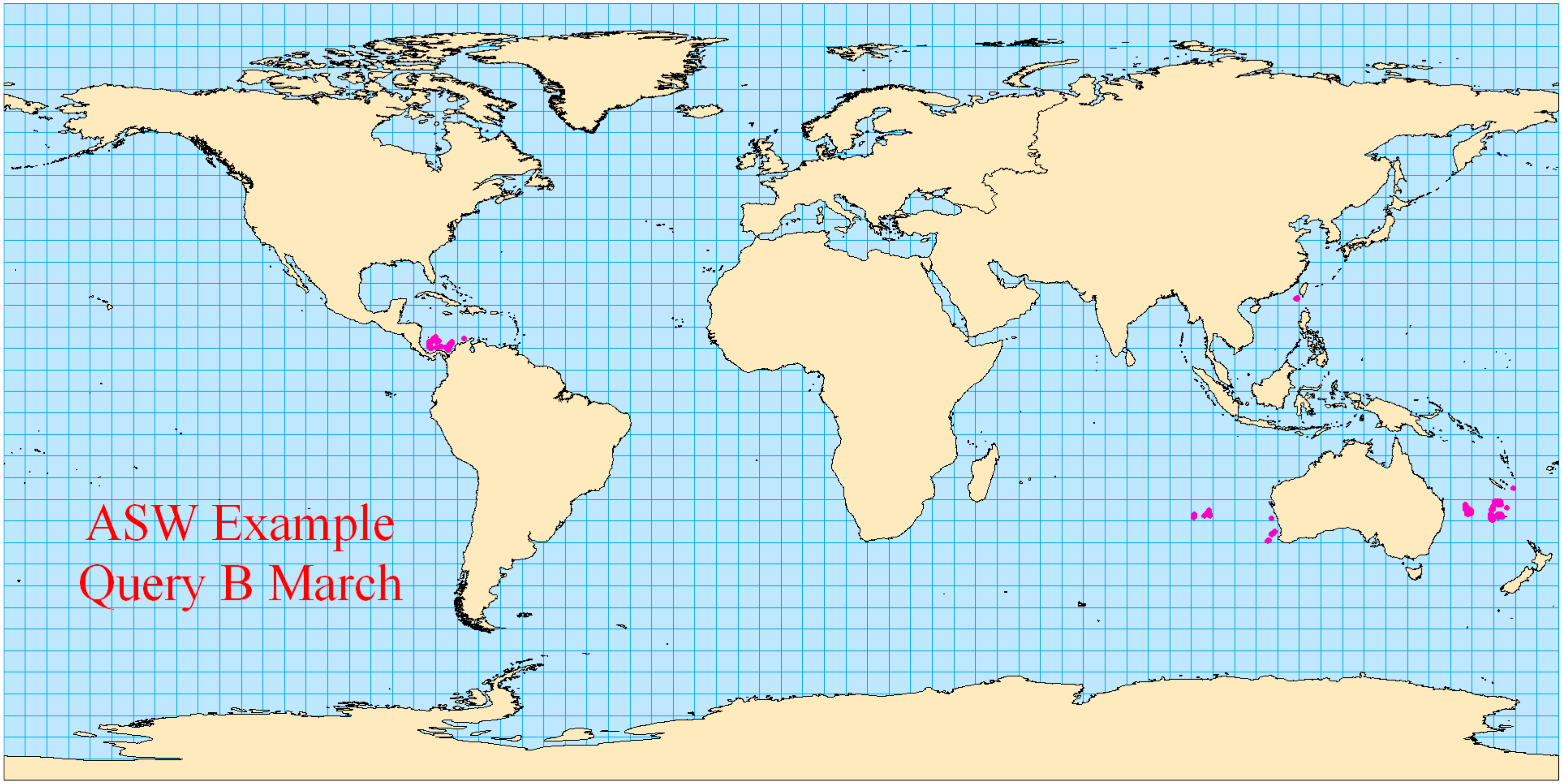

Figure 40. Query B analogous areas in March for Target Area in January.

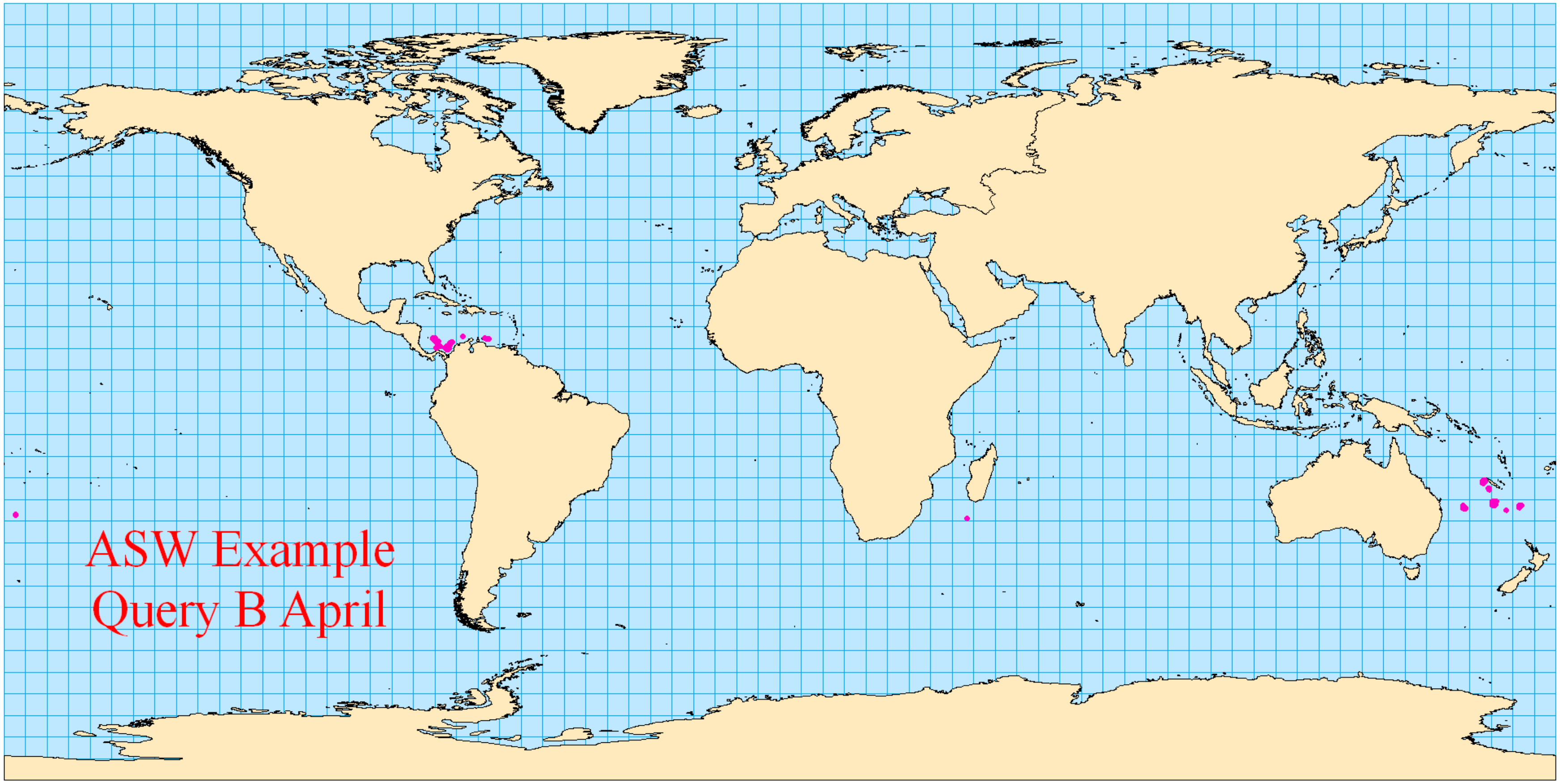

Figure 41. Query B analogous areas in April for Target Area in January.

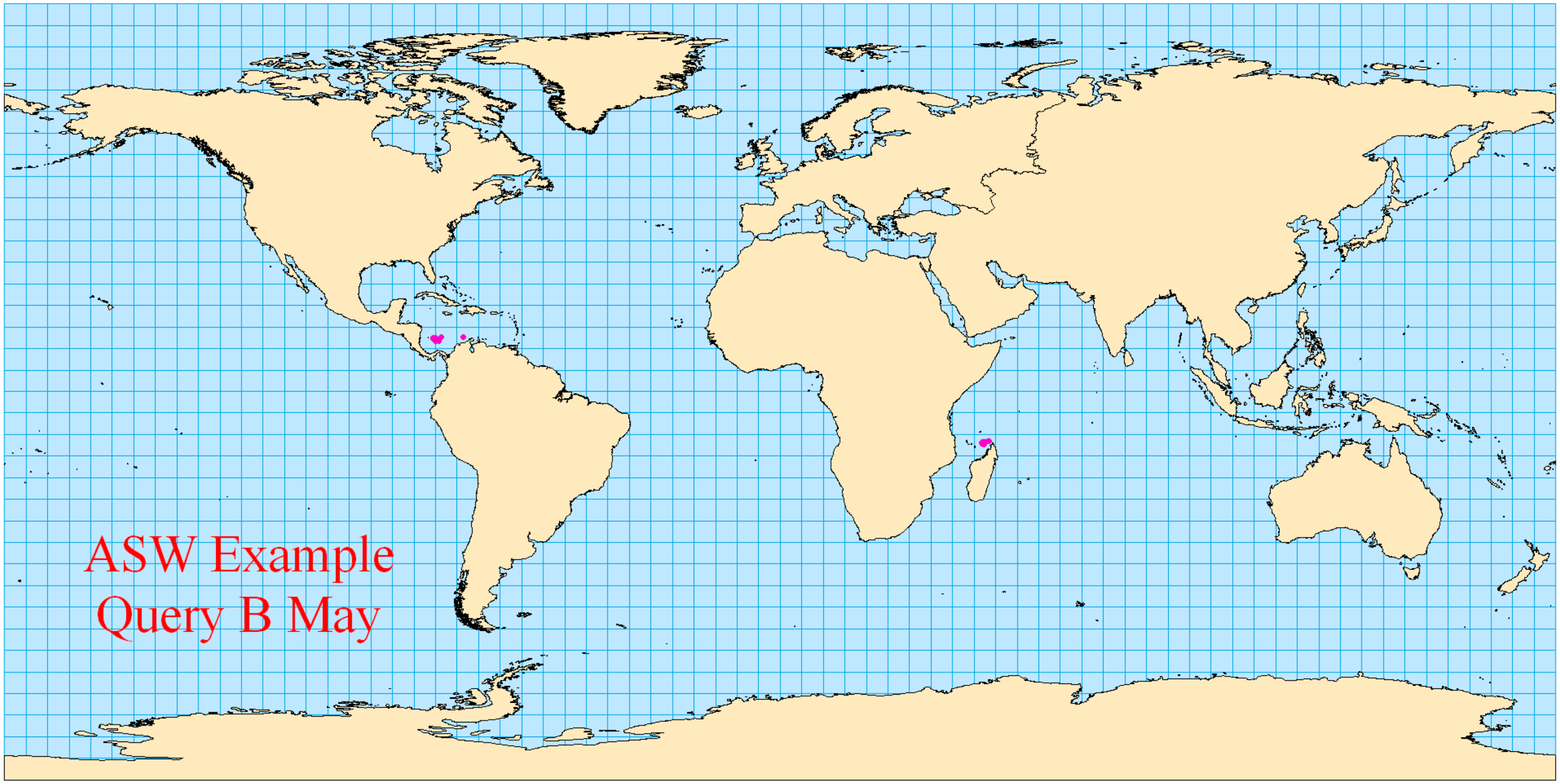

Figure 42. Query B analogous areas in May for Target Area in January.

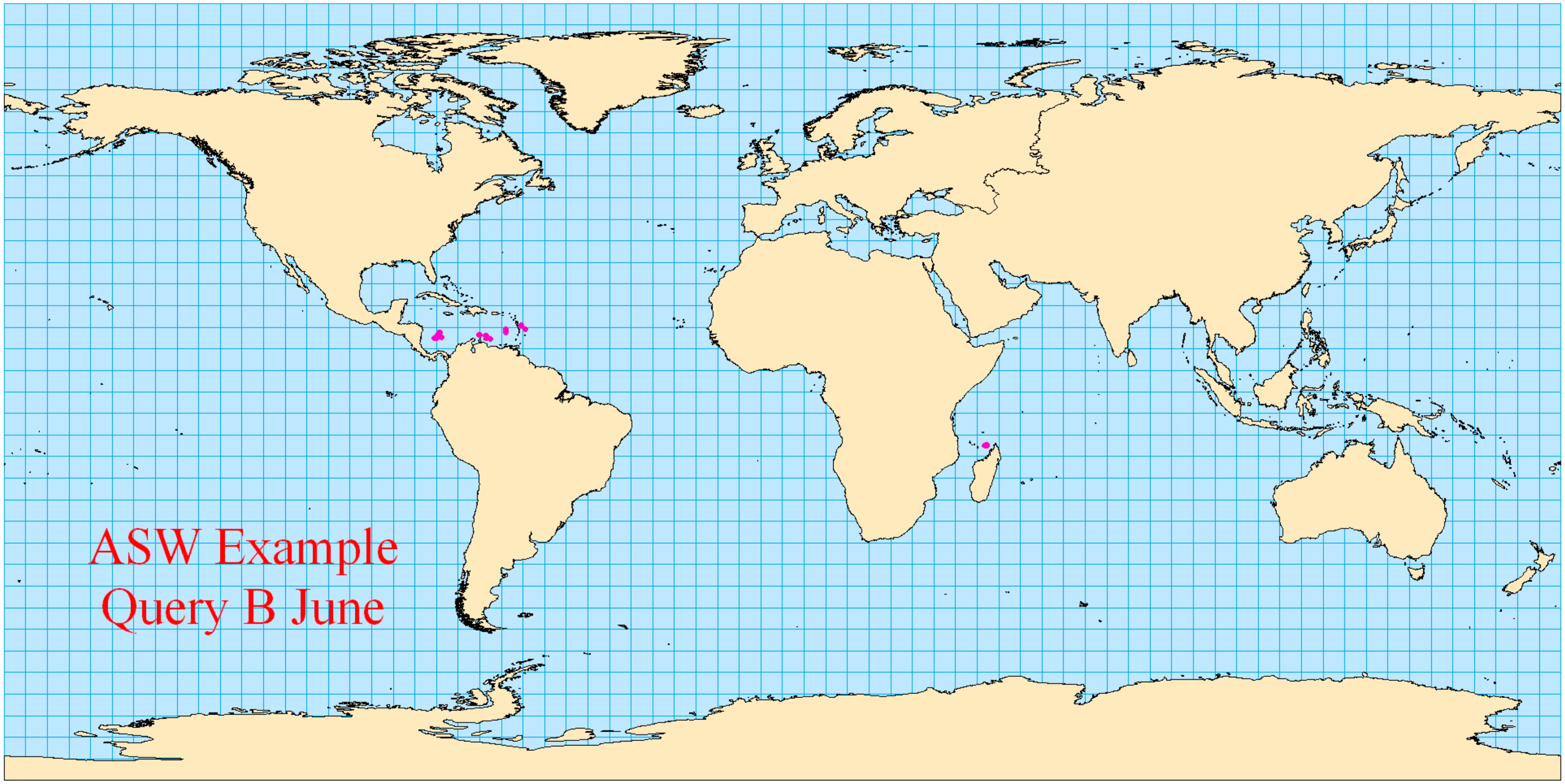

Figure 43. Query B analogous areas in June for Target Area in January.

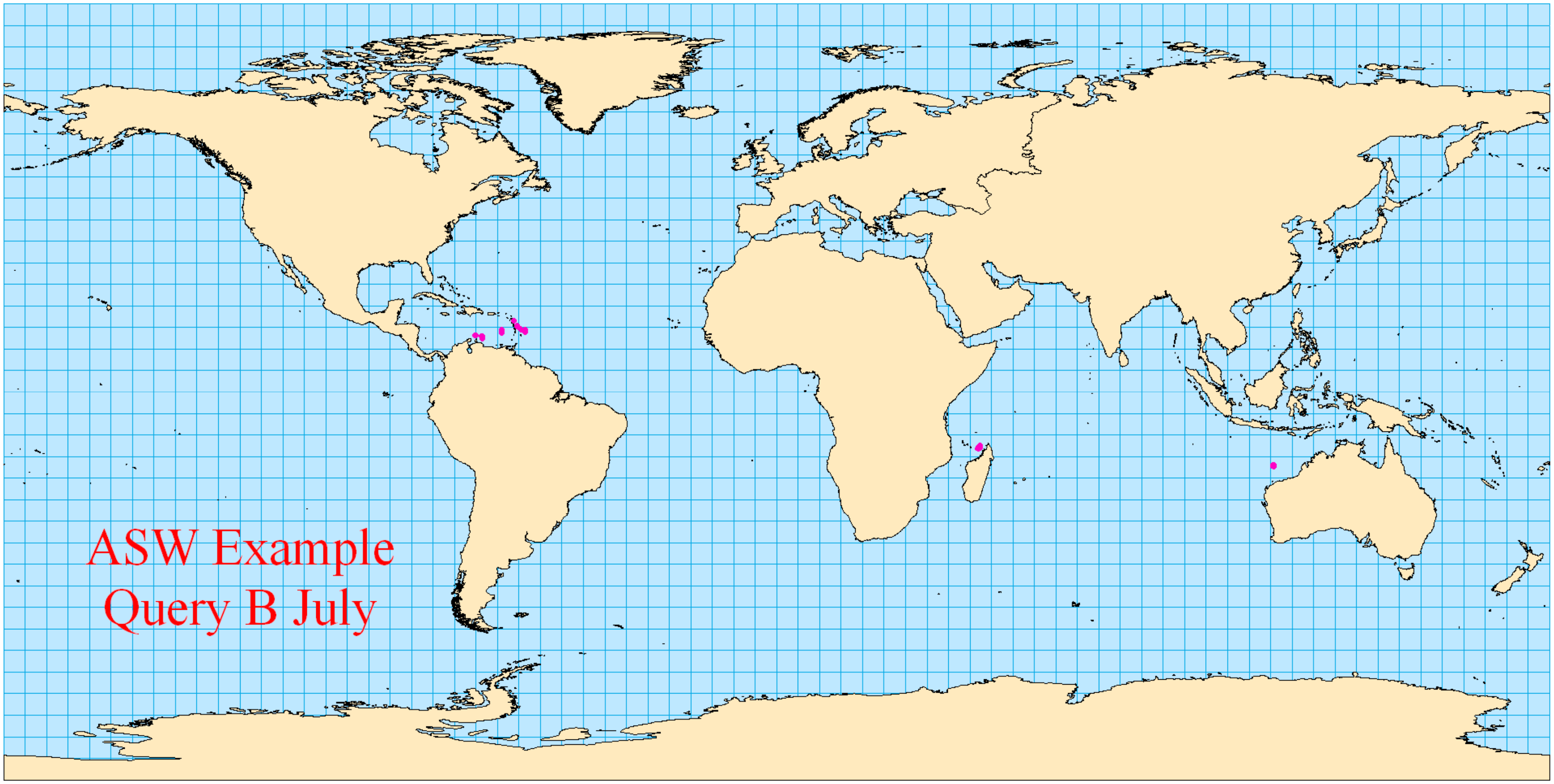

Figure 44. Query B analogous areas in July for Target Area in January.

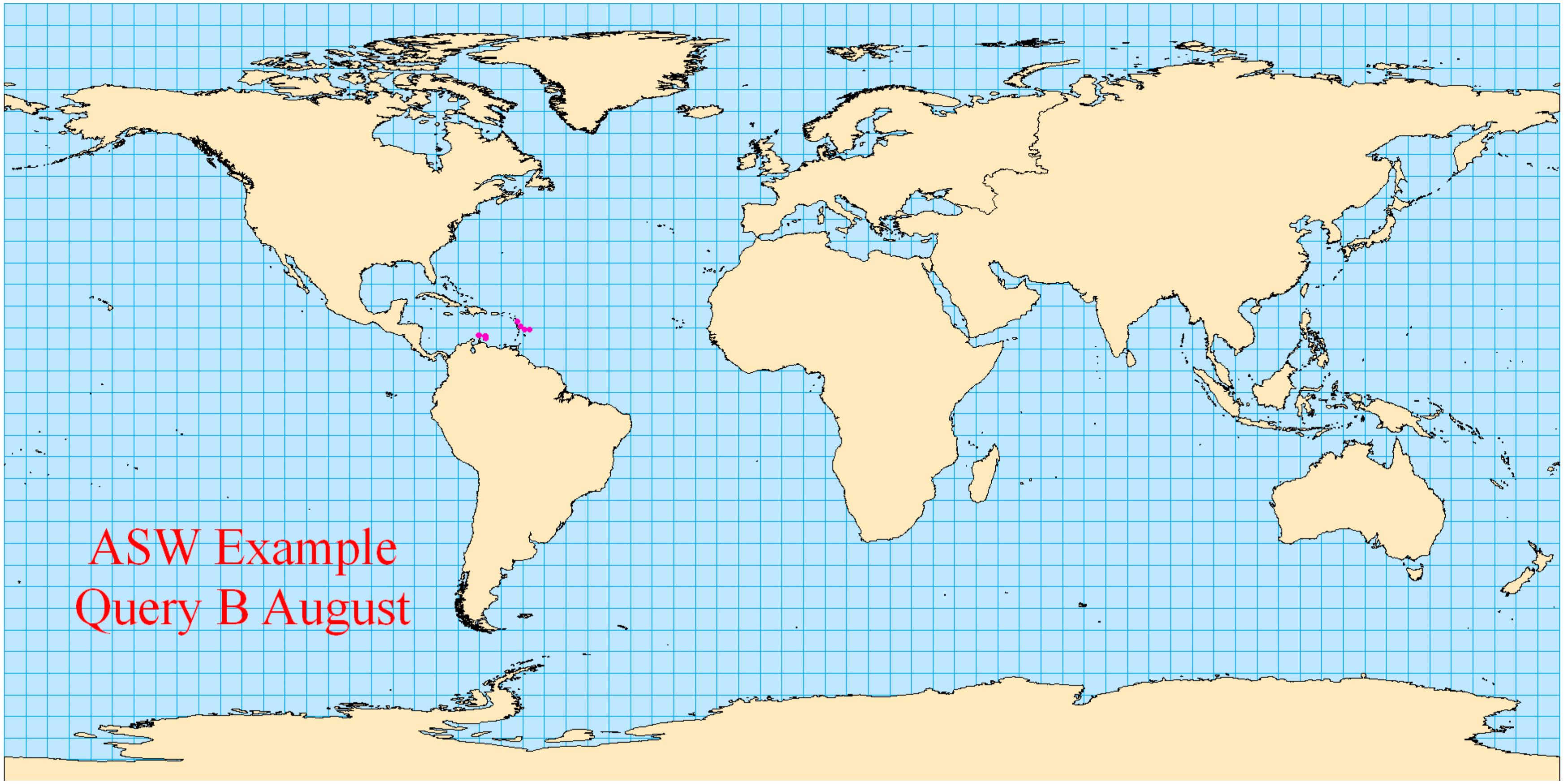

Figure 45. Query B analogous areas in August for Target Area in January.

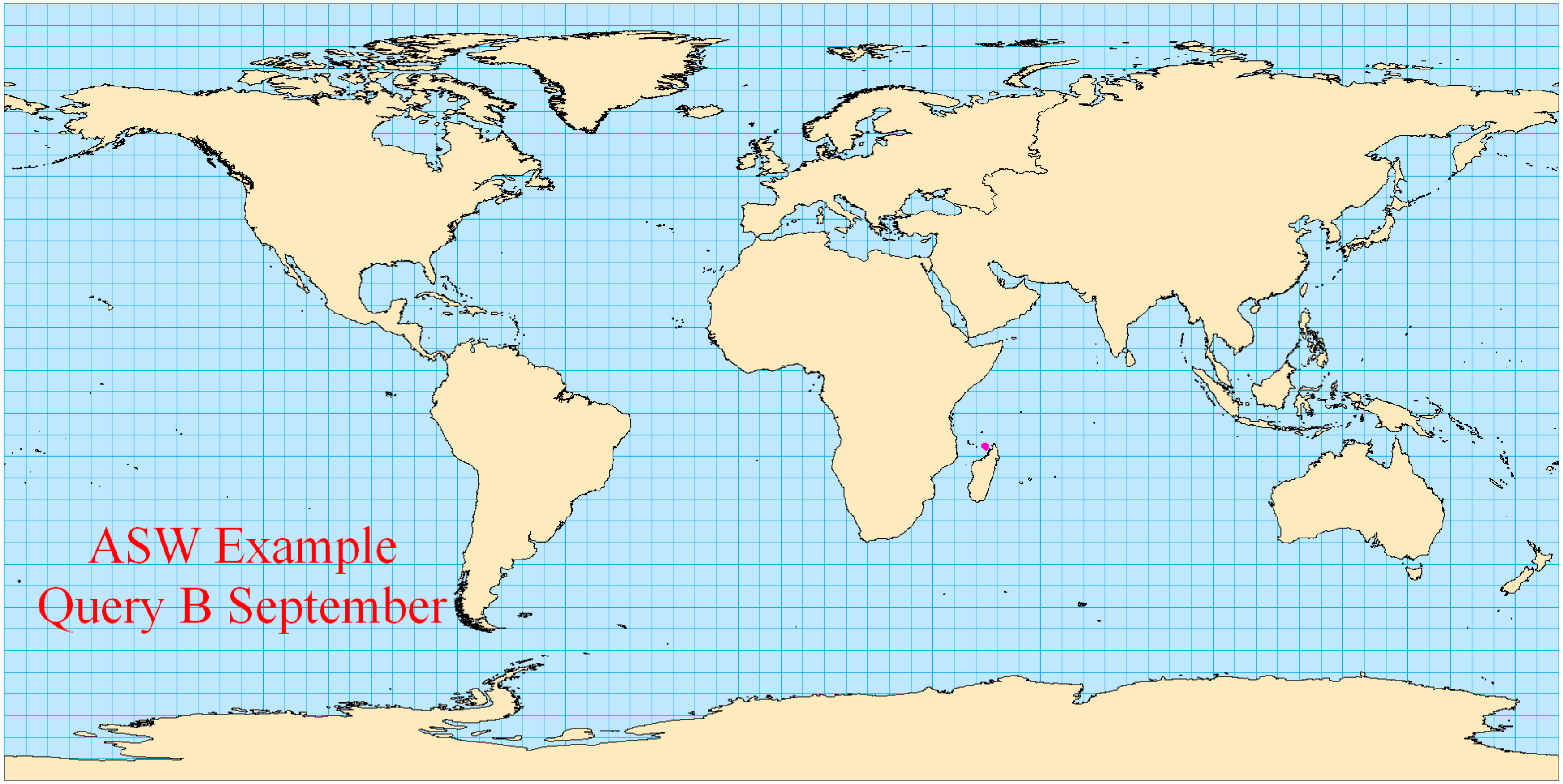

Figure 46. Query B analogous areas in September for Target Area in January.

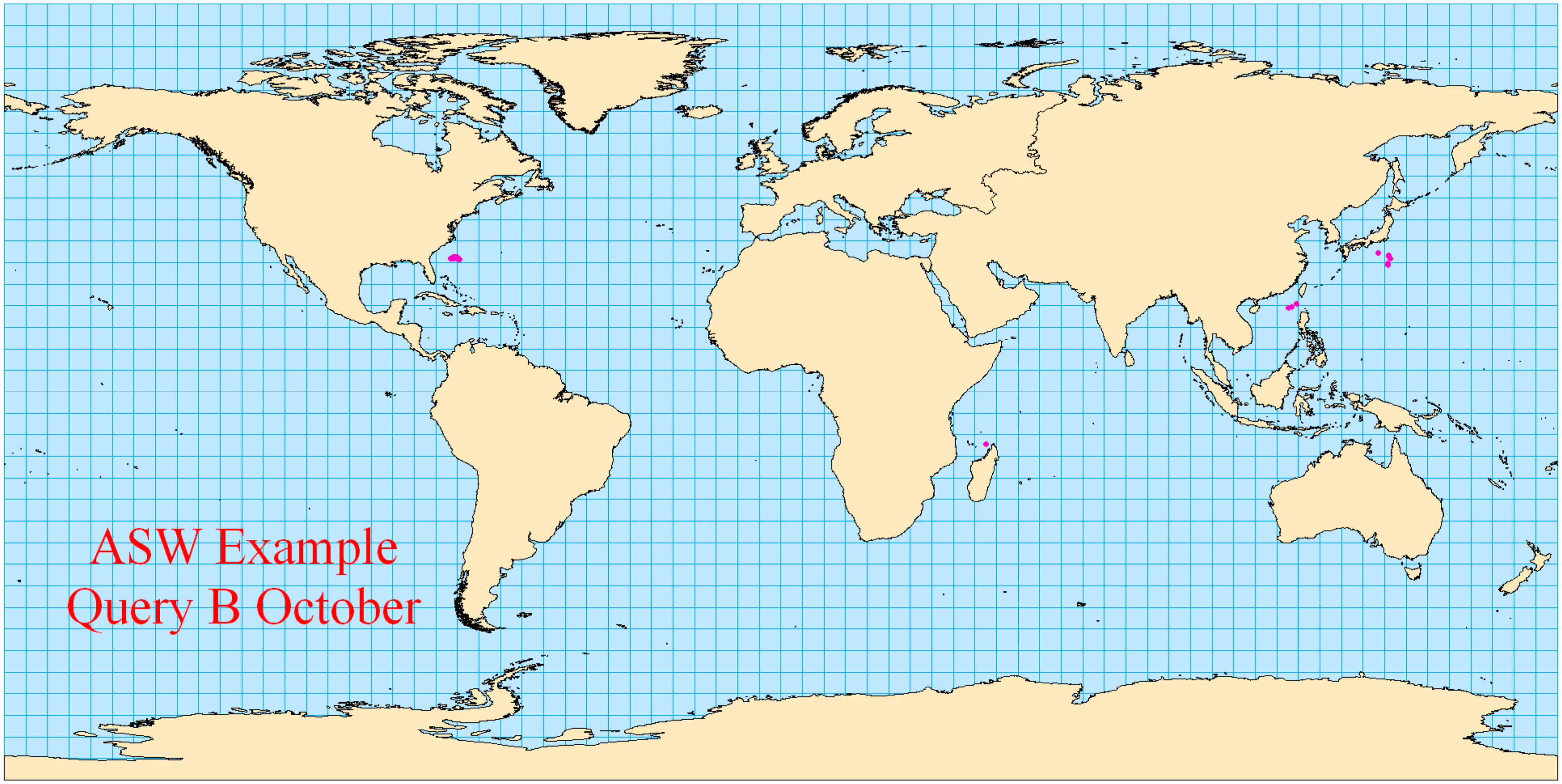

Figure 47. Query B analogous areas in October for Target Area in January.

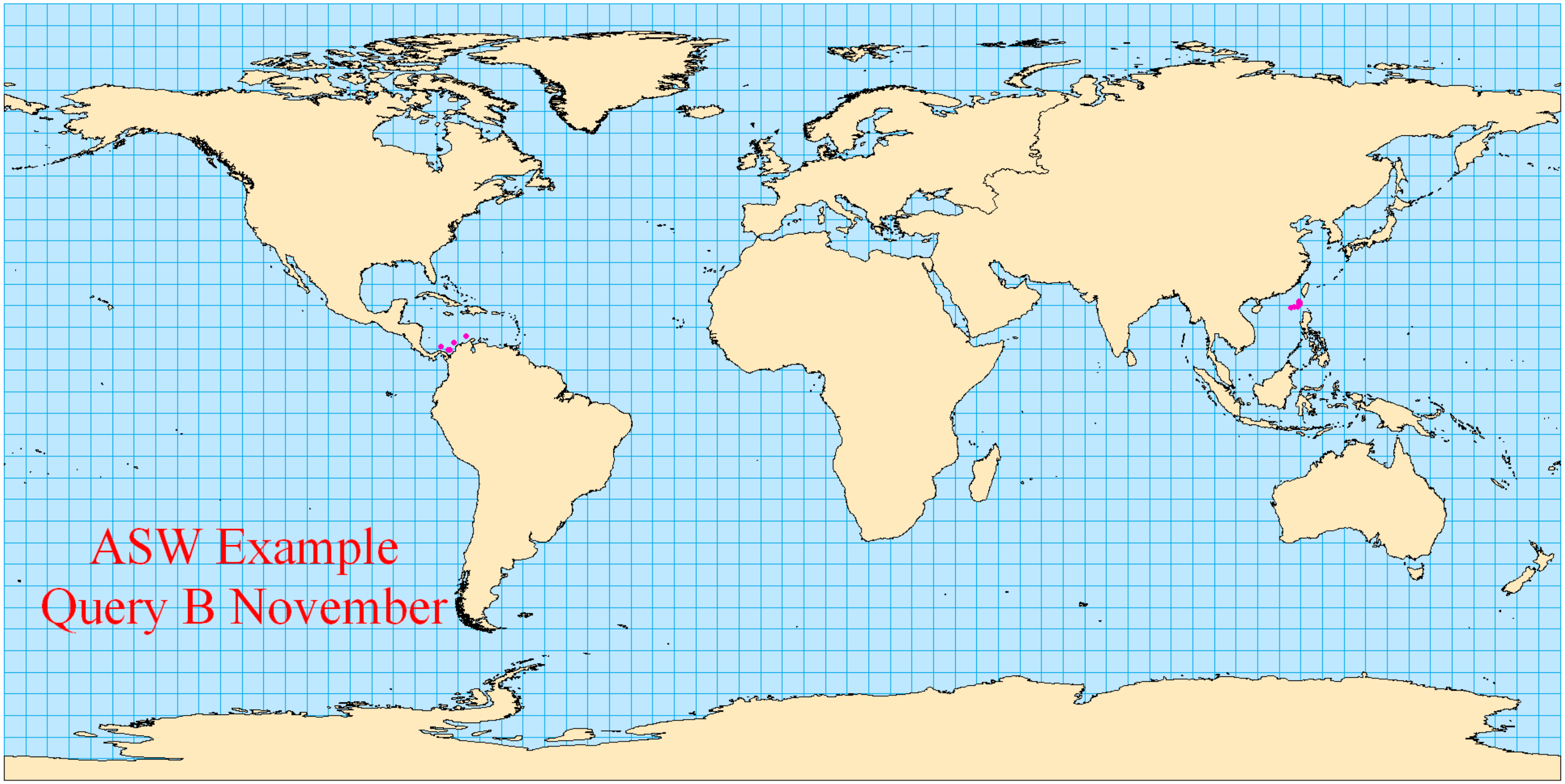

Figure 48. Query B analogous areas in November for Target Area in January.

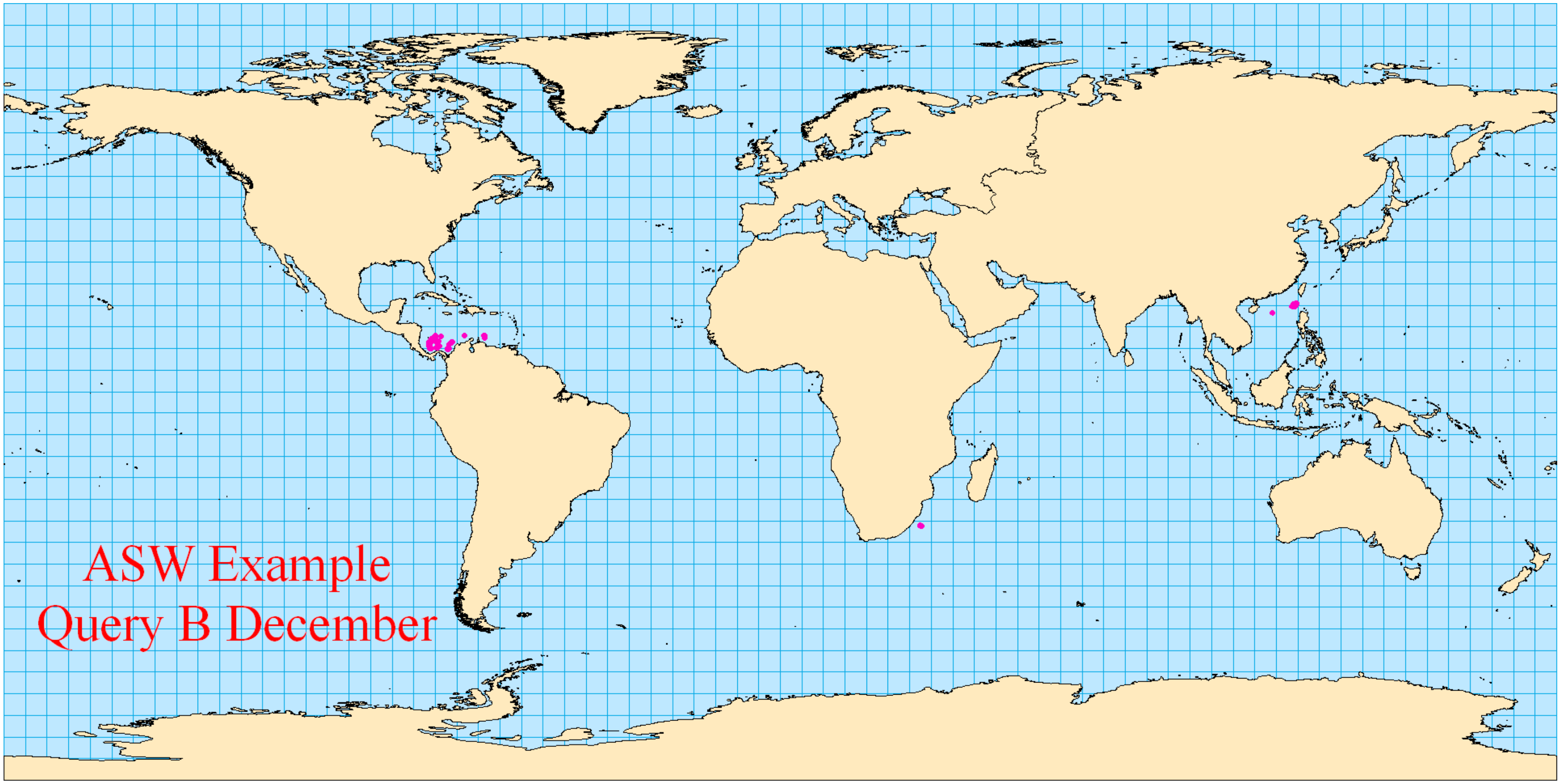

Figure 49. Query B analogous areas in December for Target Area in January.

2. Visual Comparison of Sound Speed Profiles and Ray Traces

The analogous area closest to U.S. waters for all months is chosen to validate the analogous area determination for Query B. The analogous area (31°N, -76°W) SSP is displayed on the same plot with the target area SSP from January in Figure 50. The SSPs do not match as closely as in Query A; however, the SSP descriptors used in Query B criteria match well. For example, visual inspection reveals the DSC Depth for both profiles is located at 1100-1200 meters and the MLD is at 45-50 meters. The attribute table for the Query B October analogous area confirms both depths, 1200 meters and 45 meters, respectively.

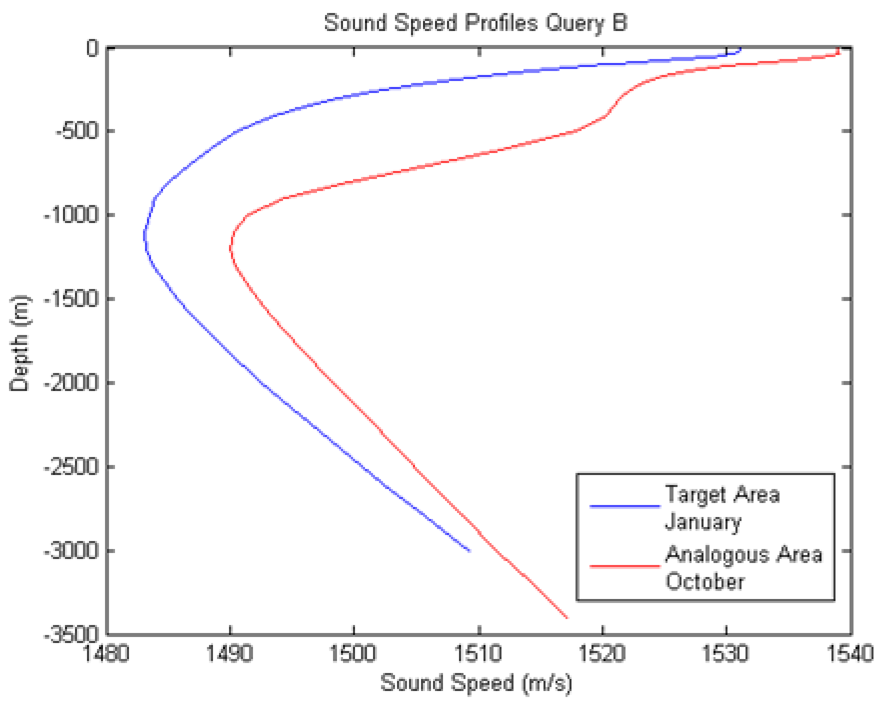

Figure 50. Sound Speed Profiles for Target Area in January (blue) and October analogous area (red) for Query B.

The same source depth and ray angles were used in the ray tracing for this analogous area and the target area. Visual analysis of the ray traces (Figures 51 and 52) of the target area and the analogous area chosen for comparison show that, like those in Query A, they are almost identical, with the exception being the shift to the right by approximately 3 km in the analogous area ray trace. This shift can be attributed to the difference in bottom depth between the two areas; it can easily be seen that if the target area depth were several hundred meters deeper, the ray traces would shift right and parallel those of the analogous area.

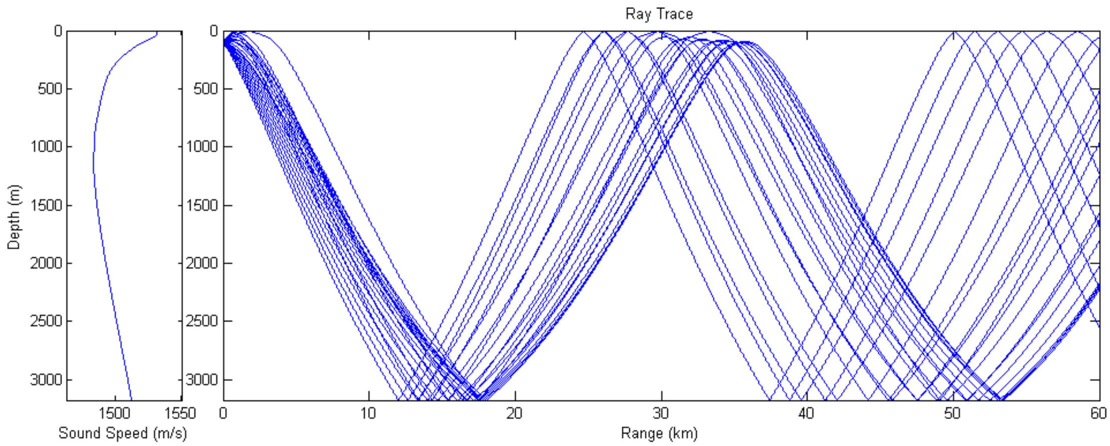

Figure 51. Query B ray trace for Target Area in January.

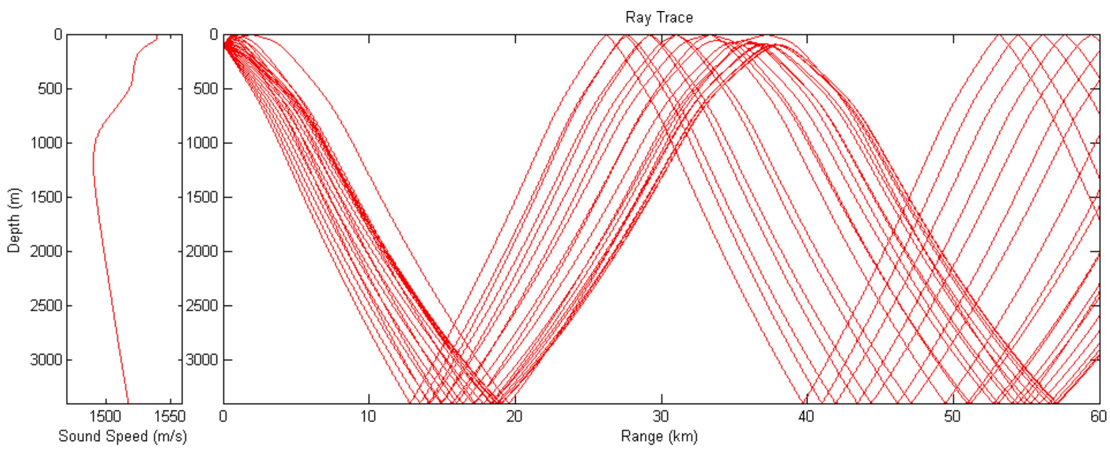

Figure 52. Query B ray trace for October analogous area.

C. QUERY C

As expected, more analogous areas were returned for Query B than in Query A. However, with the exception of the month of October, no month returned analogous areas close to USN waters and homeports. The purpose of Query C was to see how many more analogous areas would be returned if the search criteria were relaxed. While all Deep Sound Channel parameters were assigned the "20 percent" criterion, the "30 percent" criterion was applied to MLD and Thermocline Gradient and the "40 percent" criterion applied to bottom depth, wind speed, wave height, and sediment thickness. All returned analogous areas will have parameter values within 20, 30, or 40 percent of the target area's January values.

1. ArcMap Display of Analogous Areas for Query C

Figures 53-64 display the monthly analogous areas found according to Query C. Analogous areas were returned for all months using Query C. The analogous areas are shown in magenta and can be highlighted in the attribute table to obtain the monthly total, location, and the SSP descriptor information. The number of analogous areas per month produced for Query C is: January – 277, February – 378, March – 435, April – 475, May – 176, June – 65, July – 62, August – 42, September – 54, October – 66, November – 104, and December – 179. Here, the numbers may again suggest that April provides the largest number of available options to train for the ASW mission, but the analogous areas closest to the U.S. were returned for the months of October and September. The analogous area chosen for comparison with the target area is off the east coast of the United States and is in close proximity to U.S. homeports.

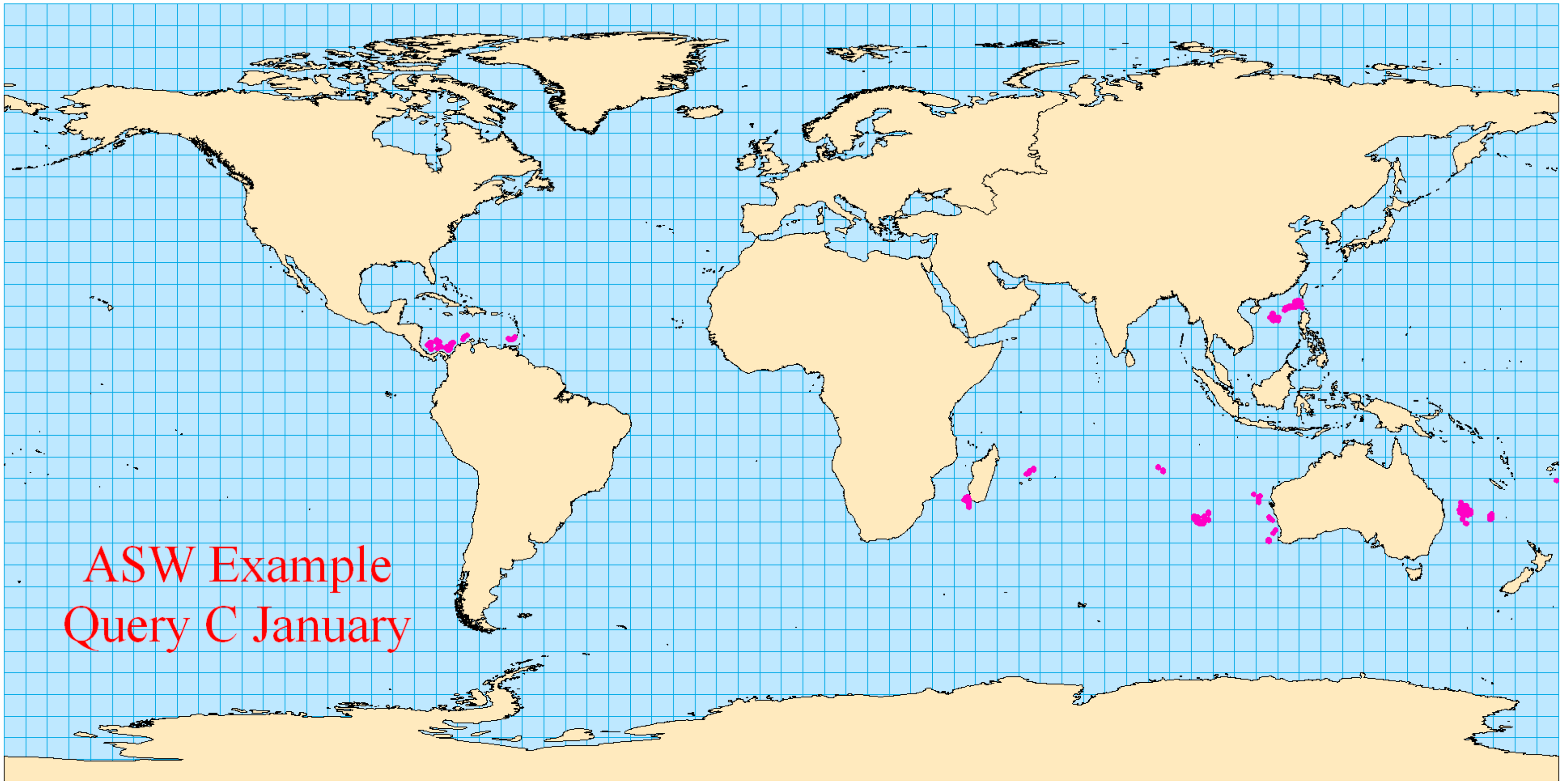

Figure 53. Query C analogous areas in January for Target Area in January.

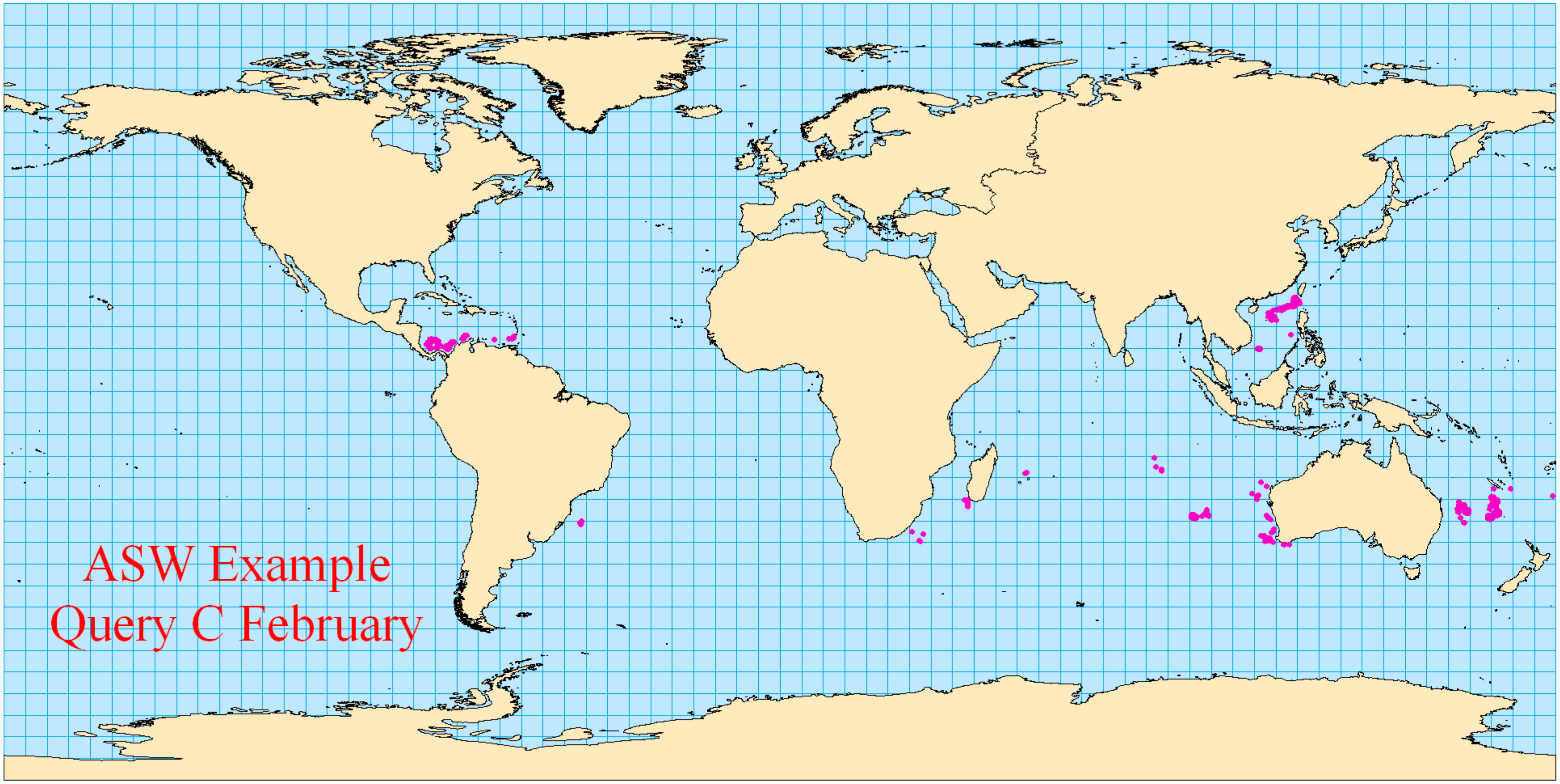

Figure 54. Query C analogous areas in February for Target Area in January.

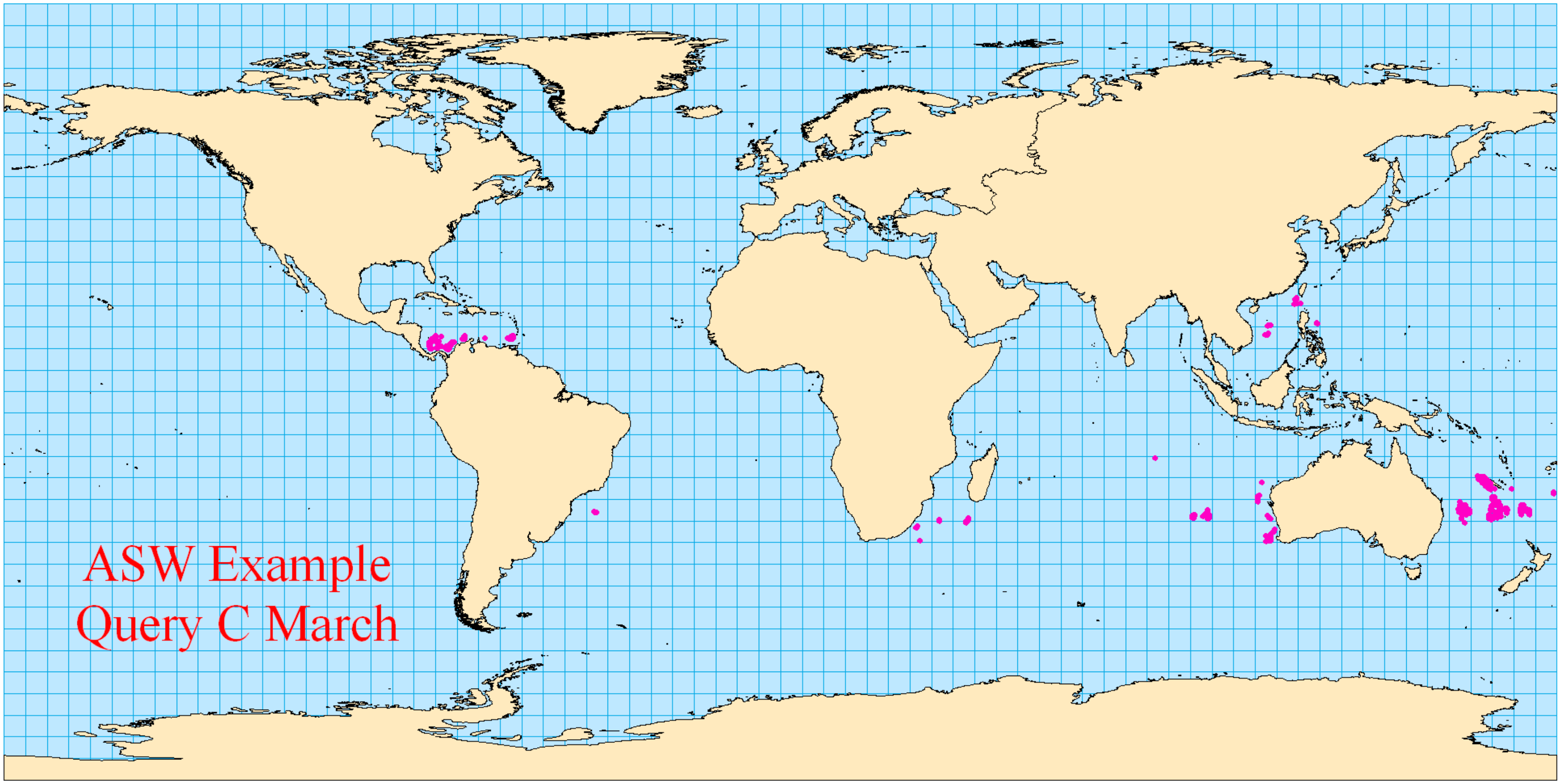

Figure 55. Query C analogous areas in March for Target Area in January.

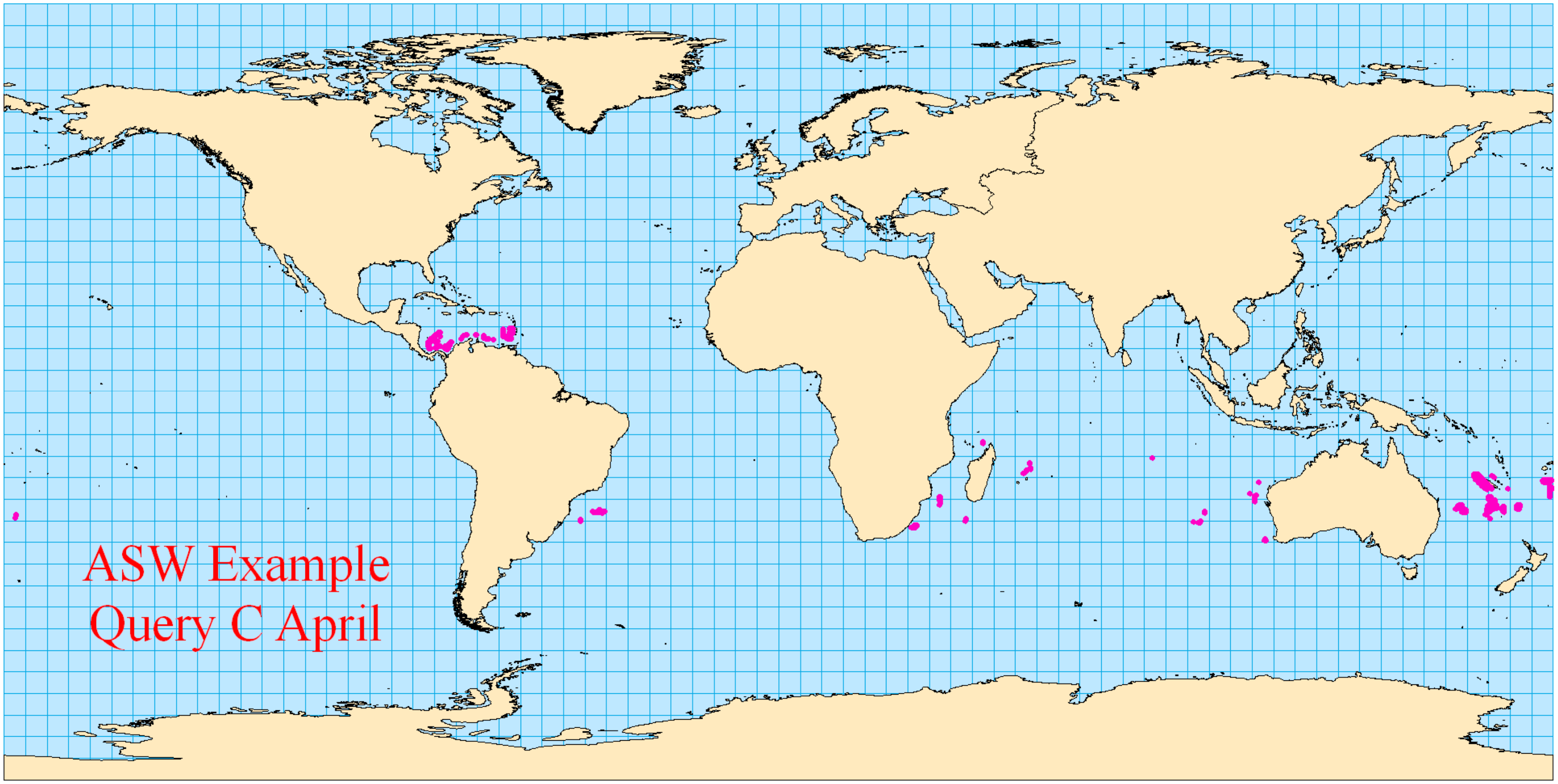

Figure 56. Query C analogous areas in April for Target Area in January.

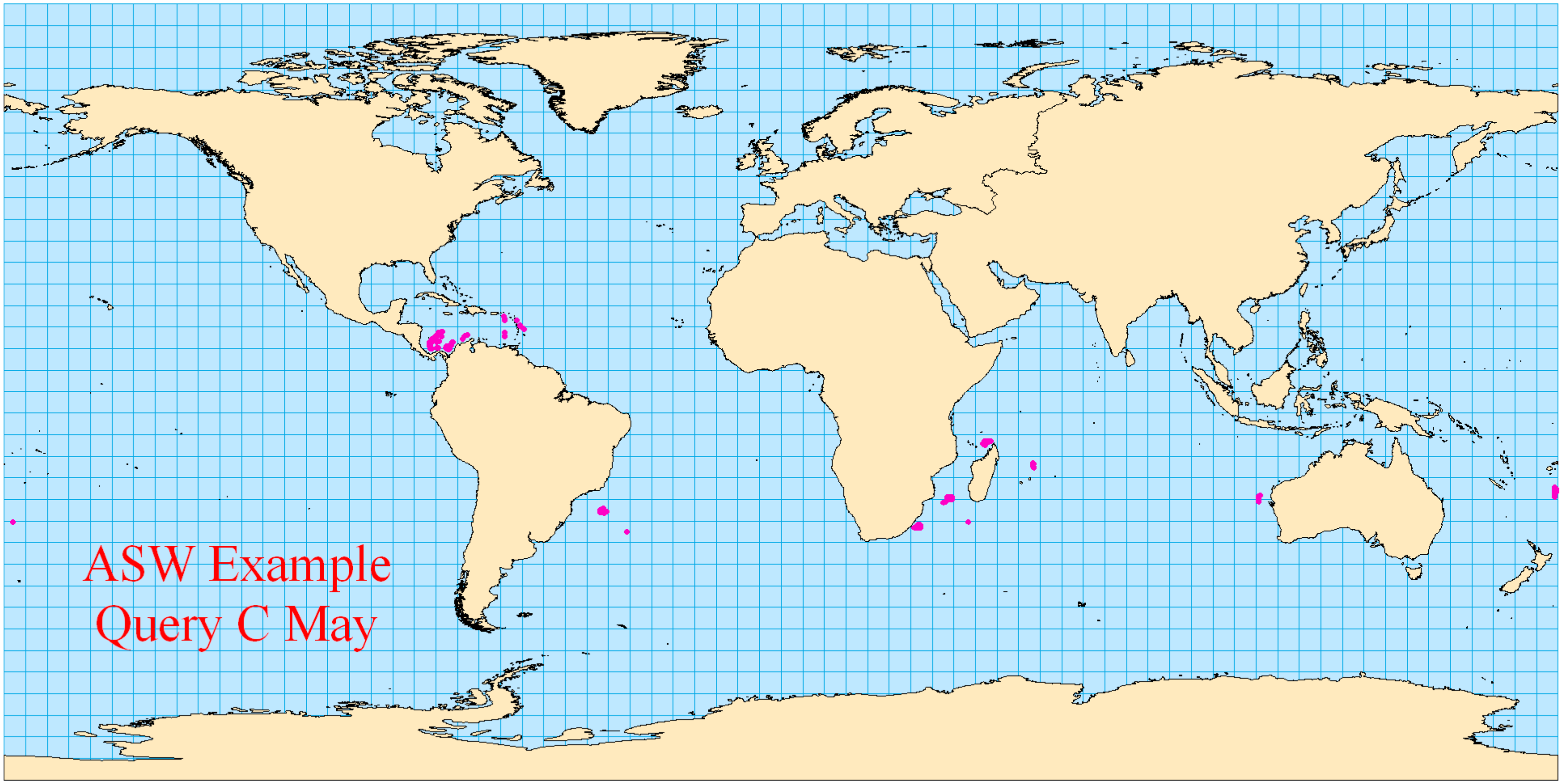

Figure 57. Query C analogous areas in May for Target Area in January.

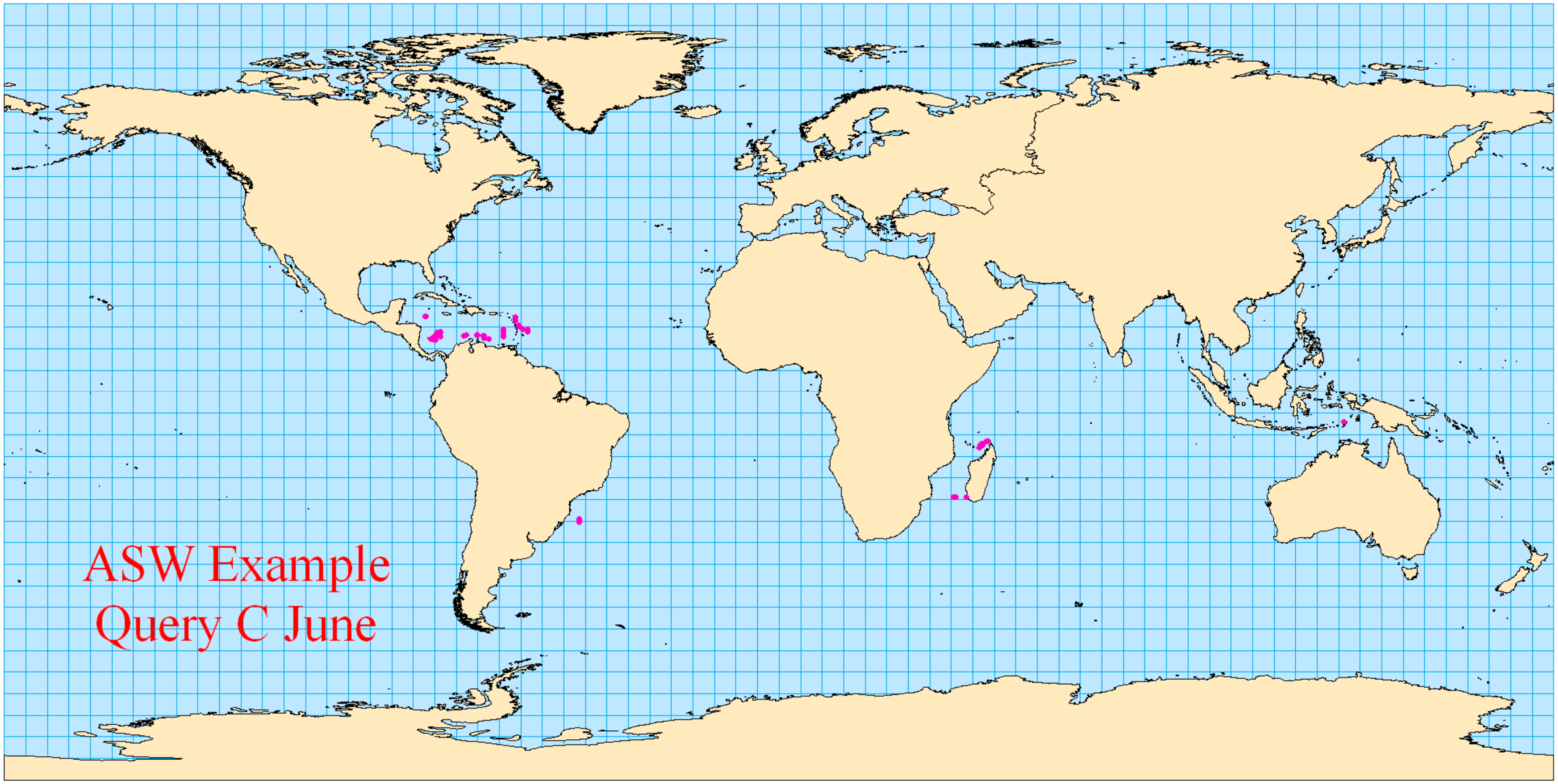

Figure 58.   Query C analogous areas in June for Target Area in January.

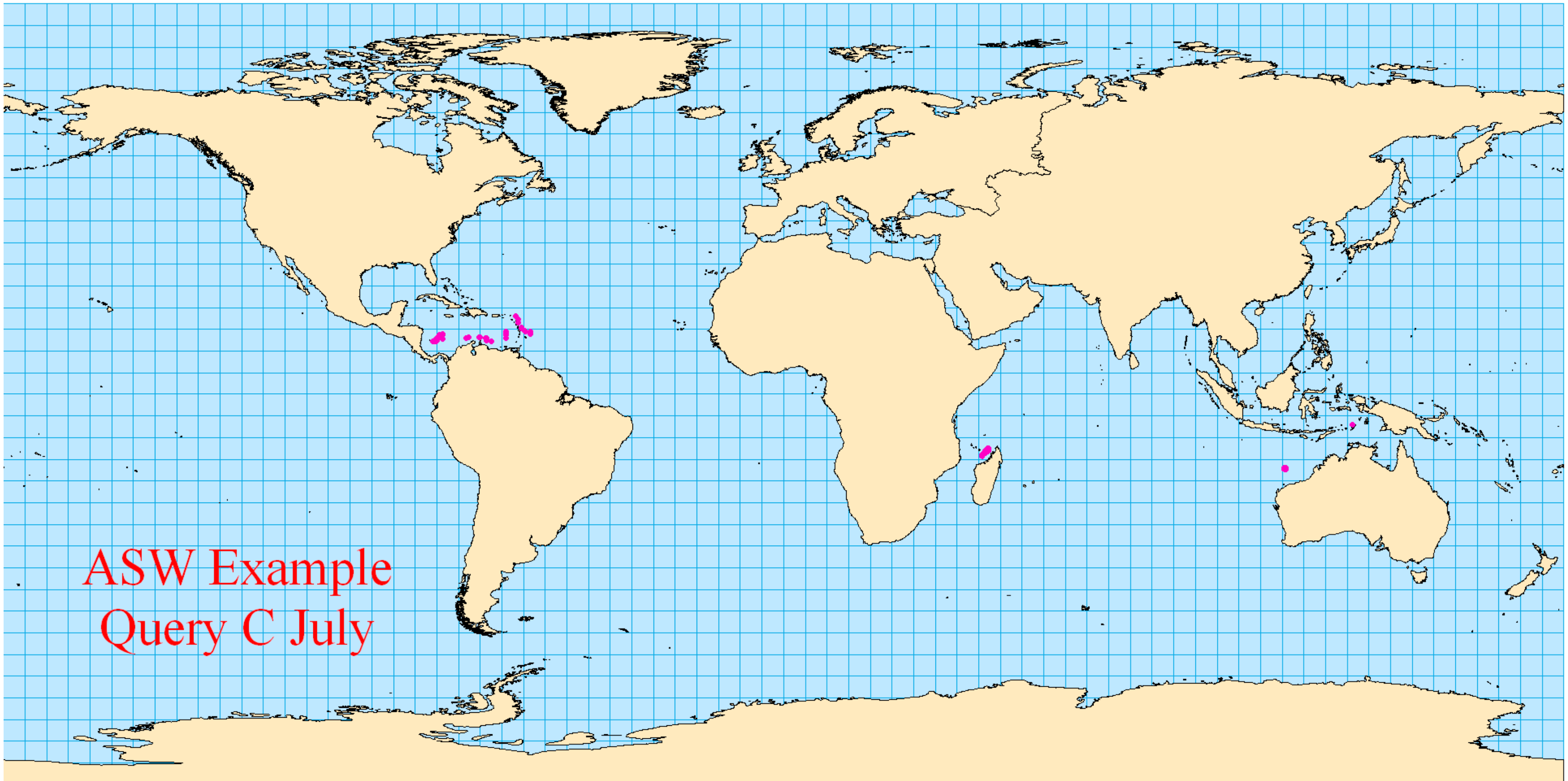

Figure 59. Query C analogous areas in July for Target Area in January.

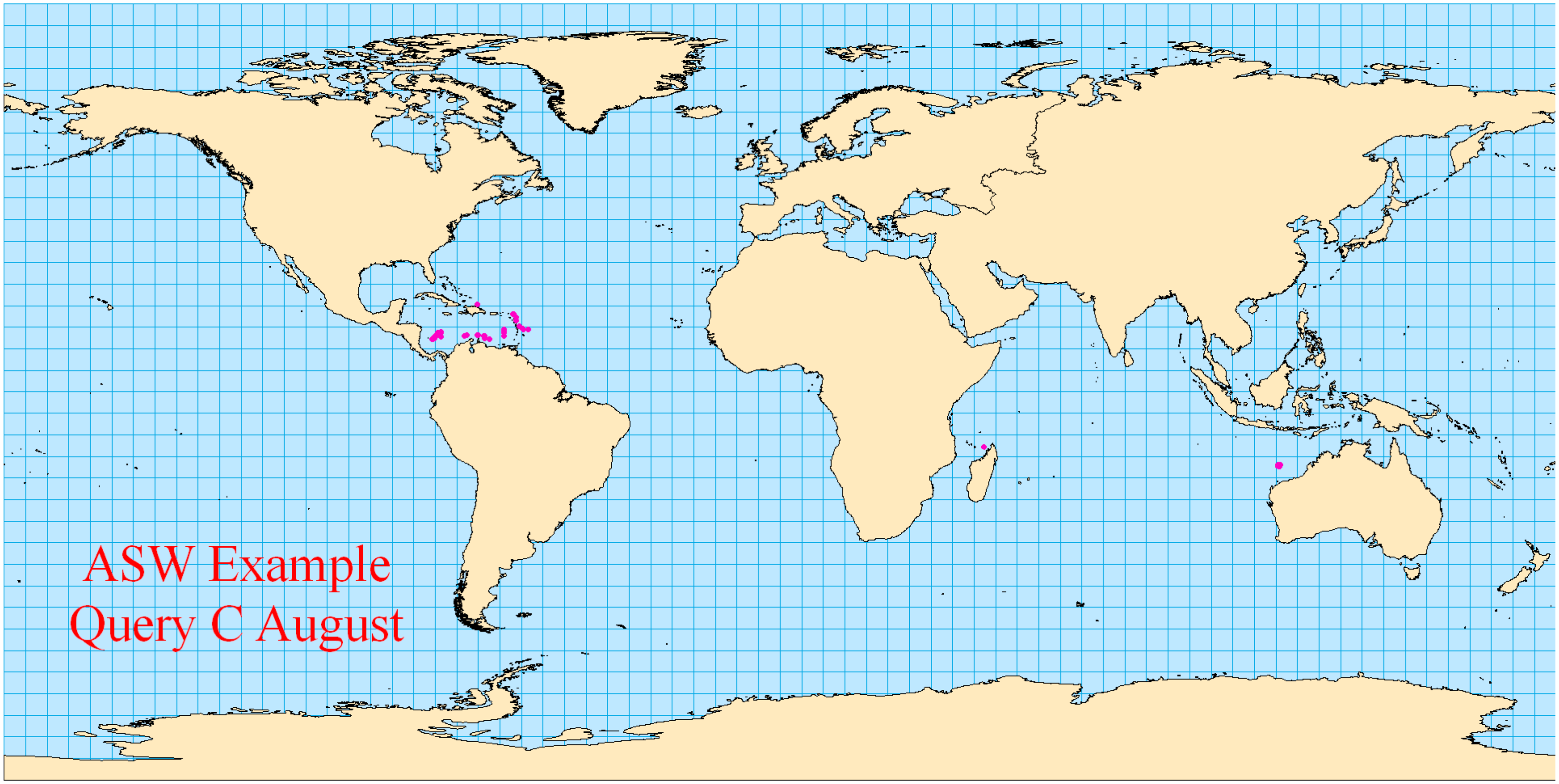

Figure 60. Query C analogous areas in August for Target Area in January.

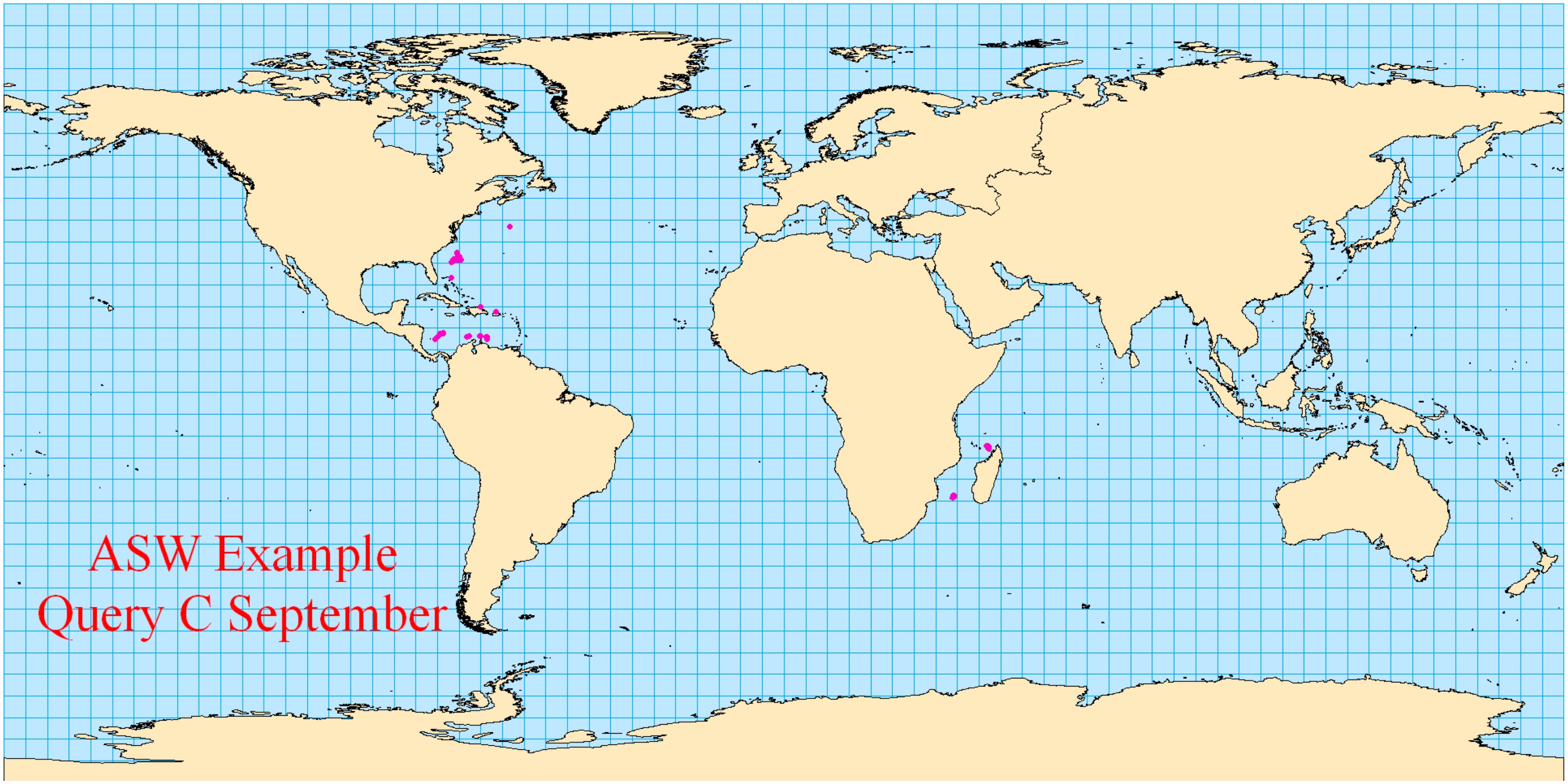

Figure 61. Query C analogous areas in September for Target Area in January.

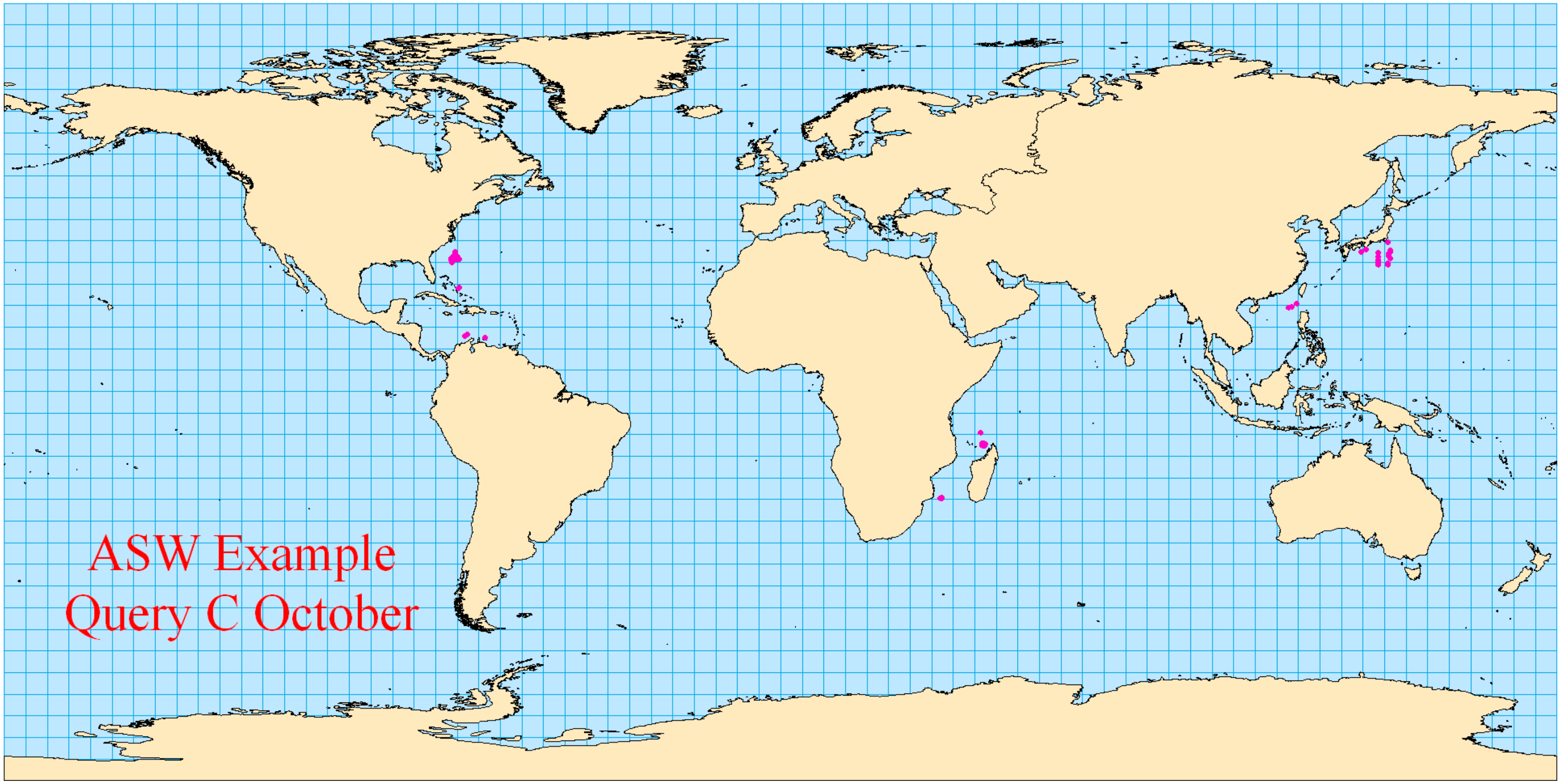

Figure 62. Query C analogous areas in October for Target Area in January.

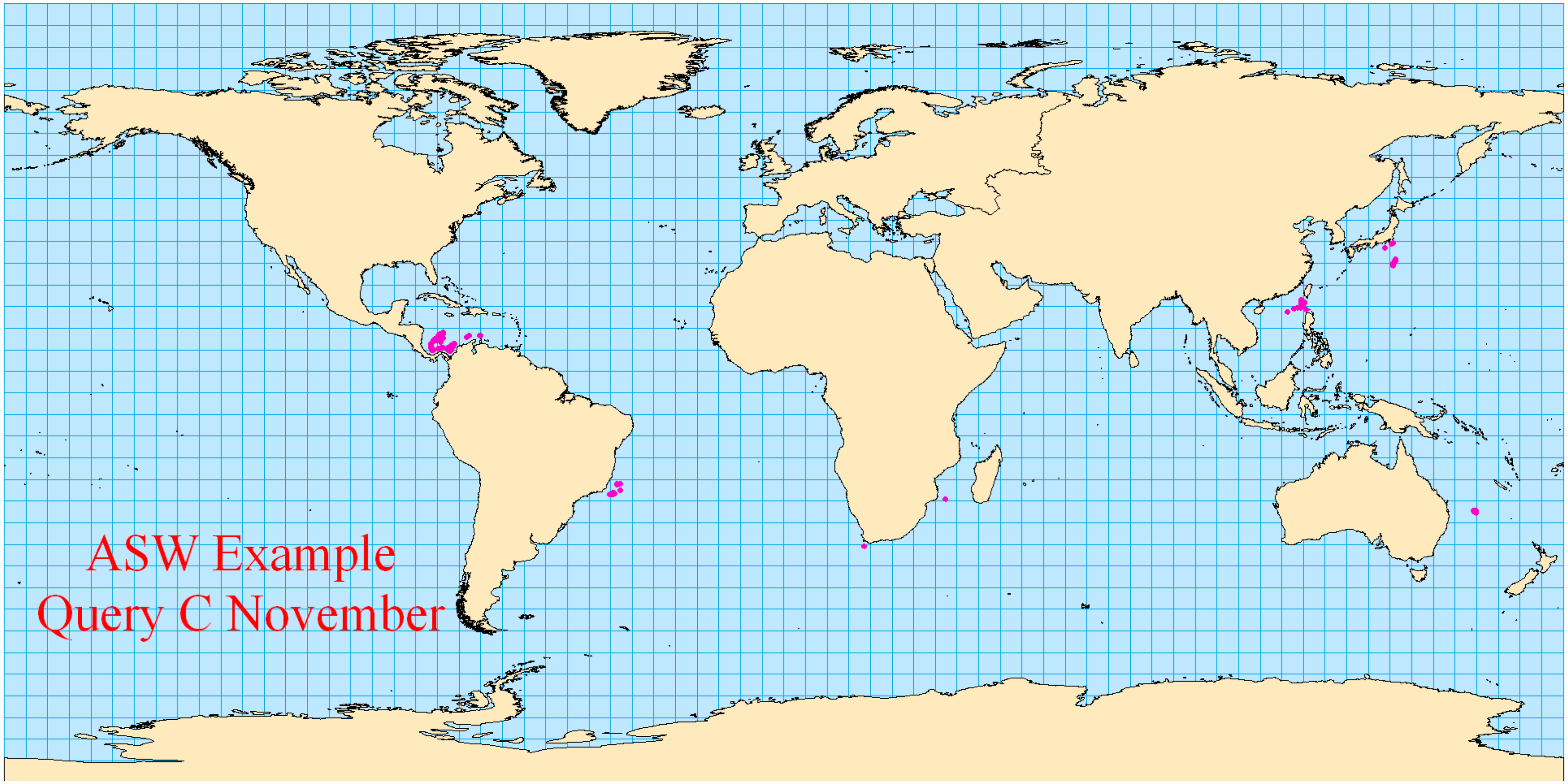

Figure 63. Query C analogous areas in November for Target Area in January.

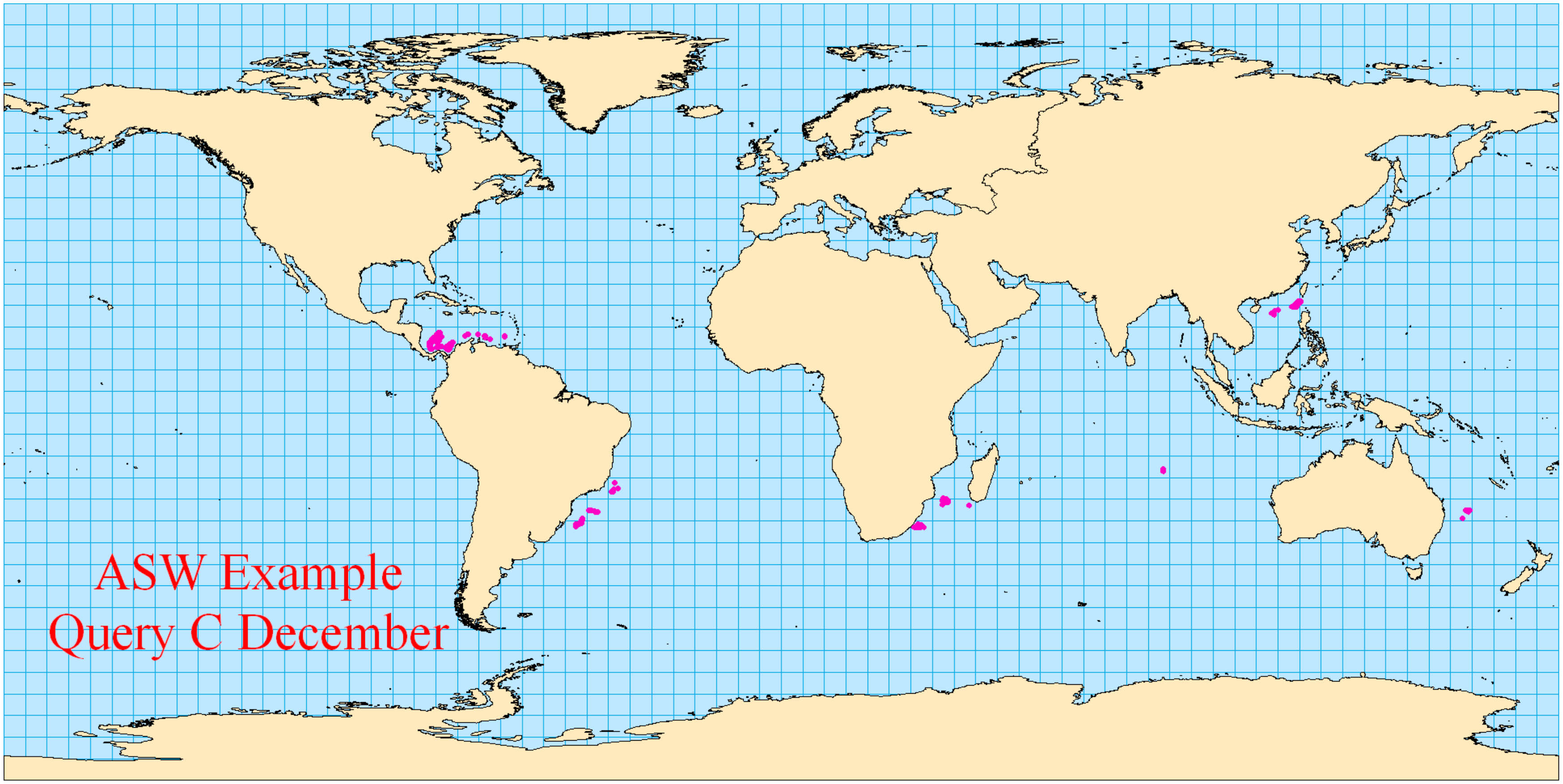

Figure 64. Query C analogous areas in December for Target Area in January.

2. Visual Comparison of Sound Speed Profiles and Ray Traces

The analogous area closest to US waters and homeports for any month is located at 30.75°N, -76.5°W, off the coast of the Southeastern United States. The SSPs for this location for the month of October and the target area are shown in Figure 61. The display looks identical to the SSP comparison display for Query B, with only a slight difference in the depth of the upper portion of the Deep Sound Channel. The selected analogous areas for both Query B and Query C occur during the month of October. While the locations of the analogous areas are not identical, they are adjacent to each other; it is reasonable to expect that the SSP will not change significantly over the spatial distance between the two points. Observation of the two SSPs reveals similar depths for the DSCD and MLD as in Query B; 1100-1200 meters and 45-50 meters, respectively, and is confirmed by the attribute table.

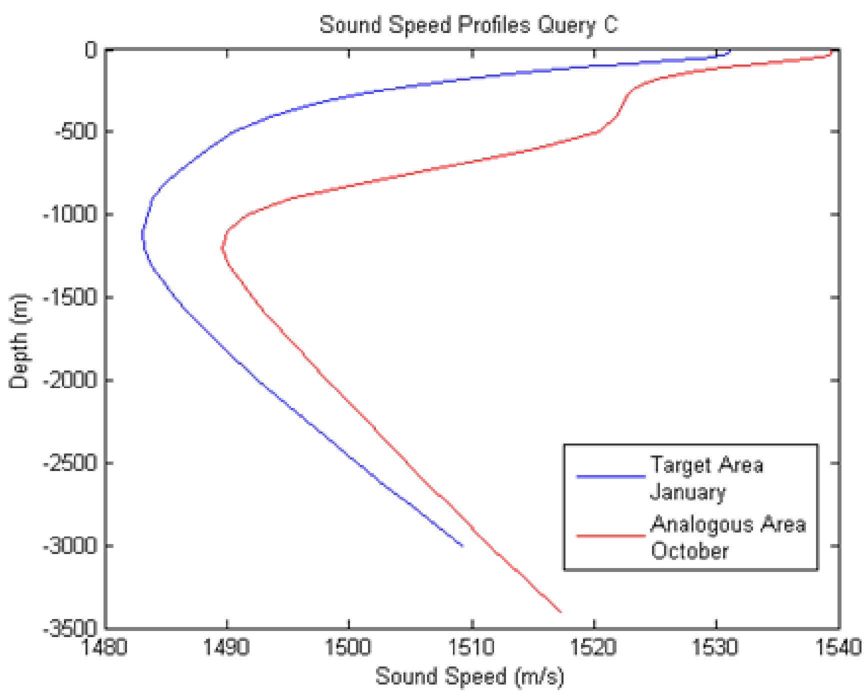

Figure 65. Sound Speed Profiles for Target Area in January (blue) and October analogous area (red) for Query C.

The ray traces, with the same source depth and ray angles as before, shown in Figures 66 and 67 further confirm the chosen analogous area to be representative of the target area in January. For most of the range of the ray trace, the two displays are practically identical. The only difference is the offset in range of the analogous area ray trace by 2 to 3 kilometers, due the greater bottom depth.

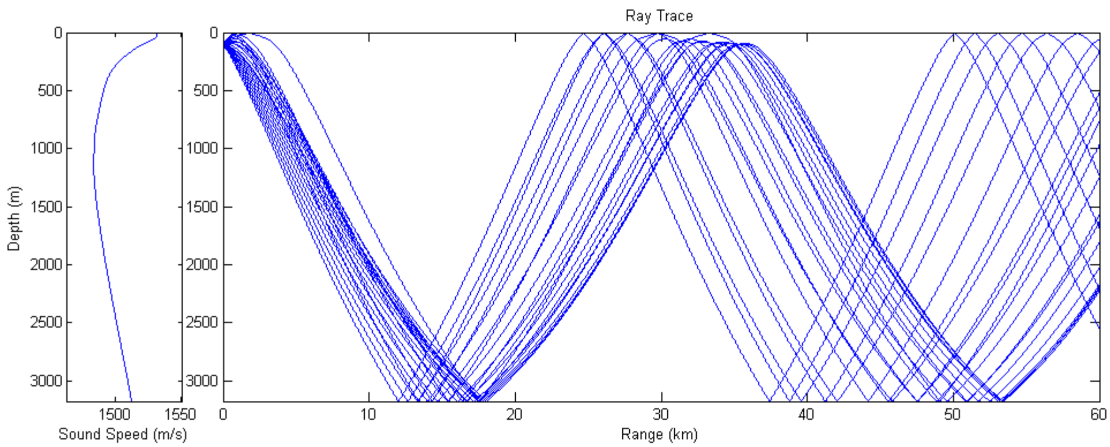

Figure 66. Query C ray trace for Target Area January Sound Speed Profile.

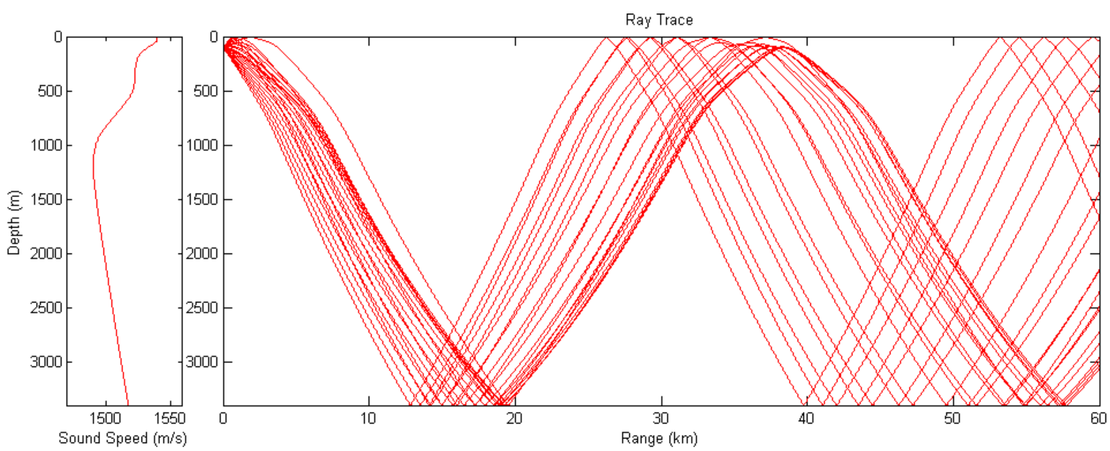

Figure 67. Query C ray trace for October analogous area Sound Speed Profile.

D. MONTHLY COMPARISON OF QUERIES A, B, AND C

The individual months for each query have been displayed but in order to show the variation in each month according to the query criteria, Figures 68 through 79 display the monthly analogous areas determined for the target area in January. The three query types used here, Query A, B, C, are displayed in yellow, blue, and magenta, respectively, and simultaneously express the increasing number of analogous areas returned as the query type changed and query ranges modified. Only January, February, and March (Figures 68-70) include Query A since all other months produced no analogous areas for that query.

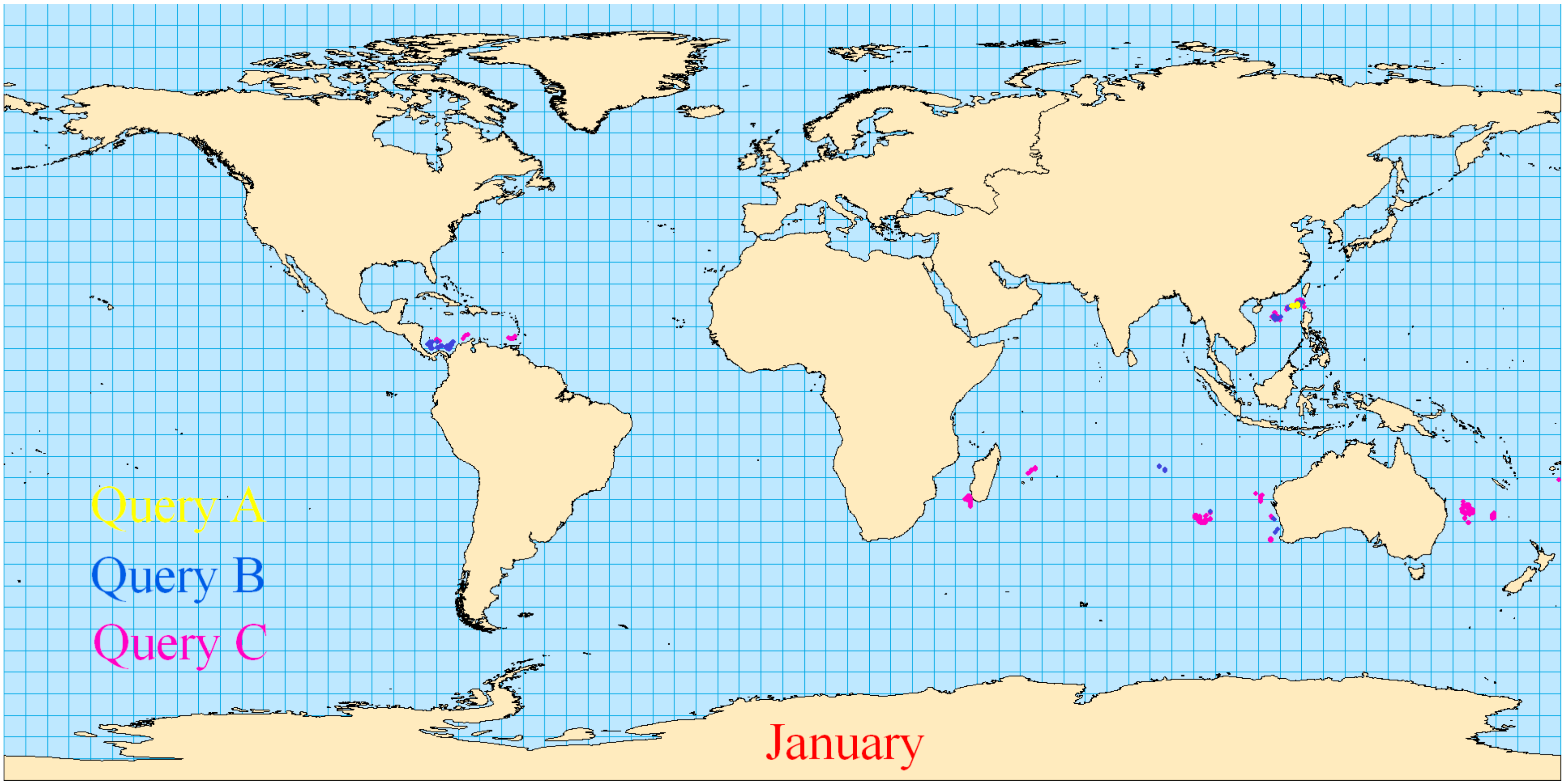

Figure 68. January analogous areas for Query A, B, & C for Target Area in January.

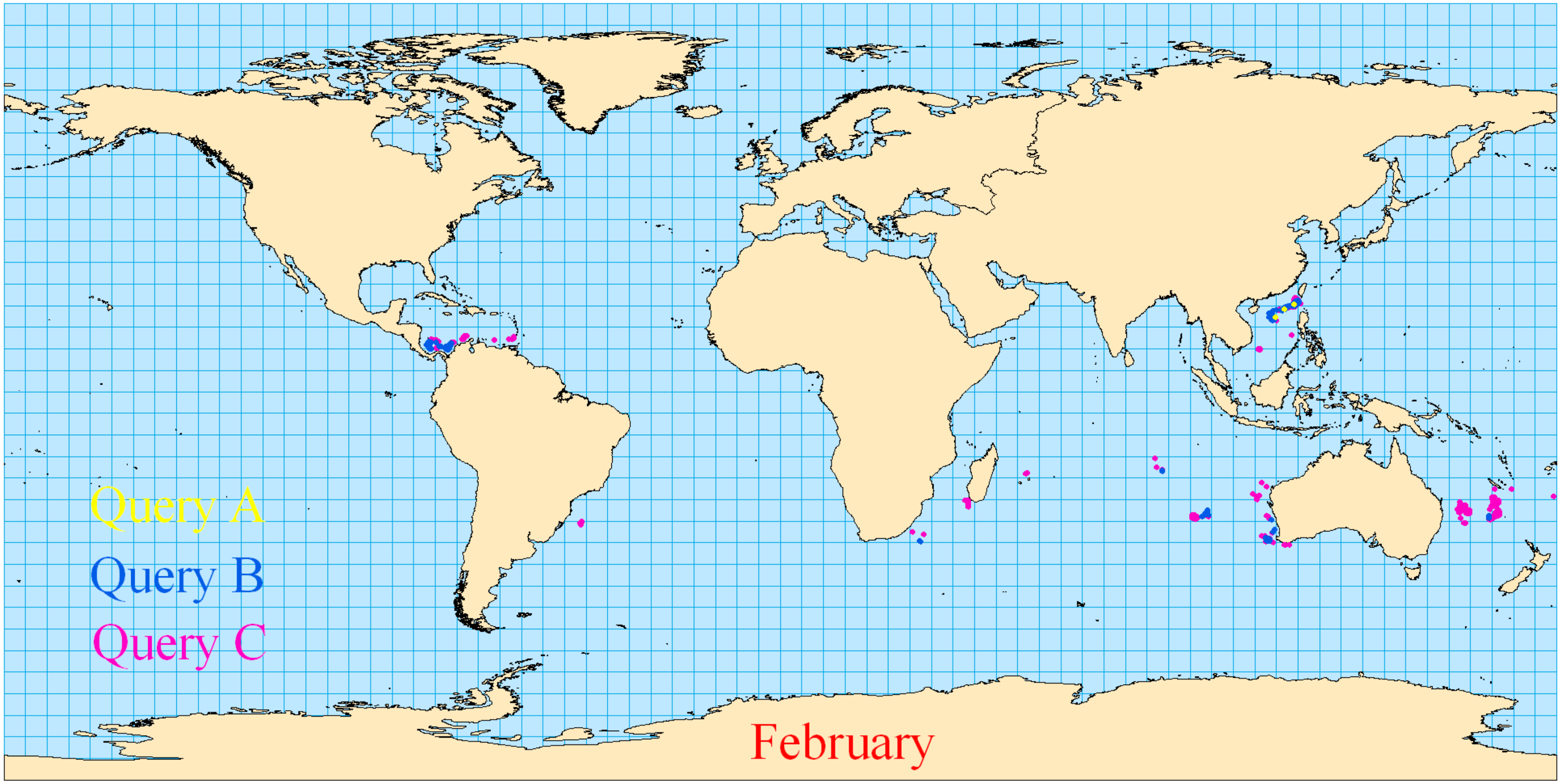

Figure 69. February analogous areas for Query A, B, & C for Target Area in January.

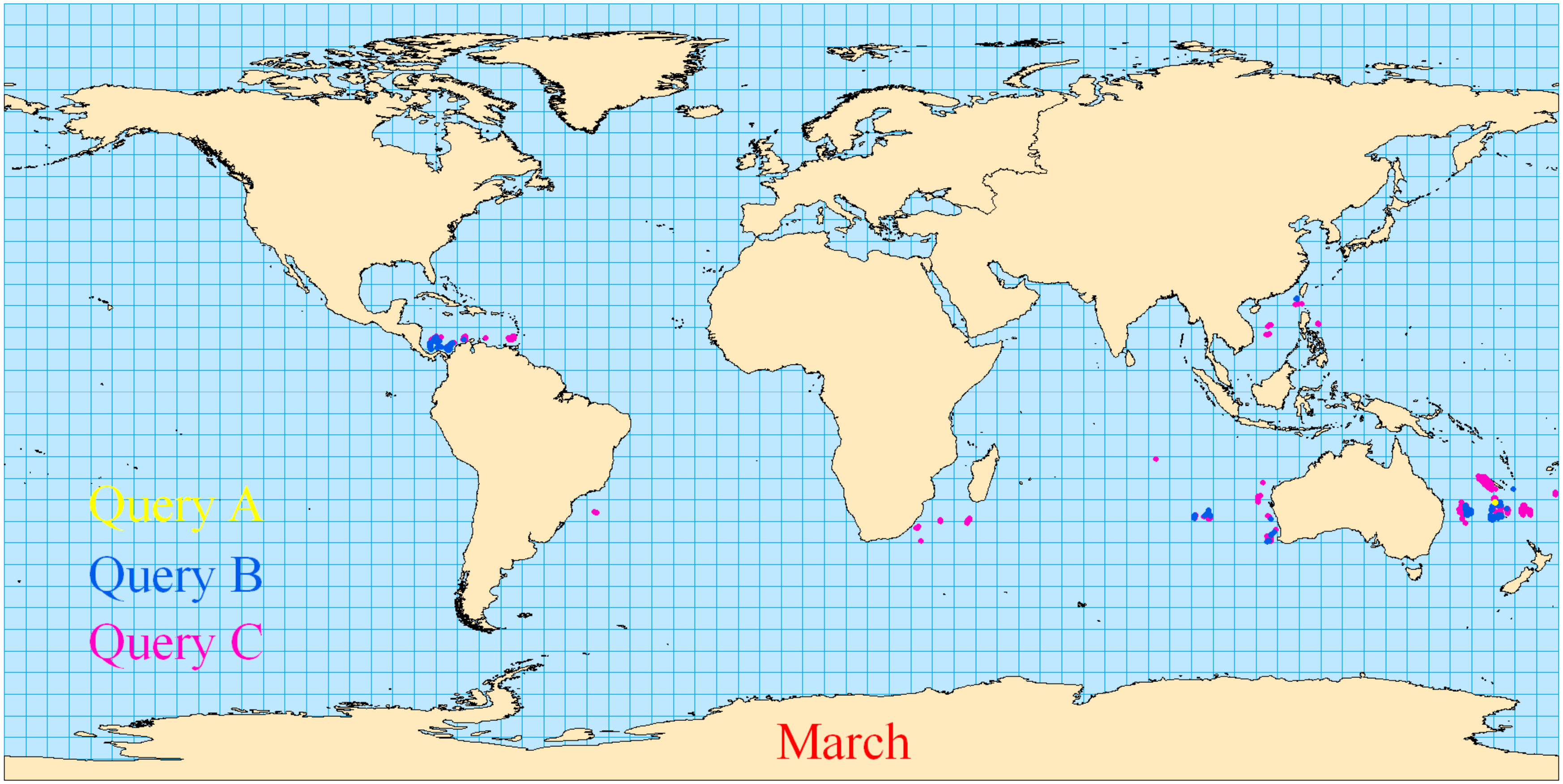

Figure 70. March analogous areas for Query A, B, & C for Target Area in January.

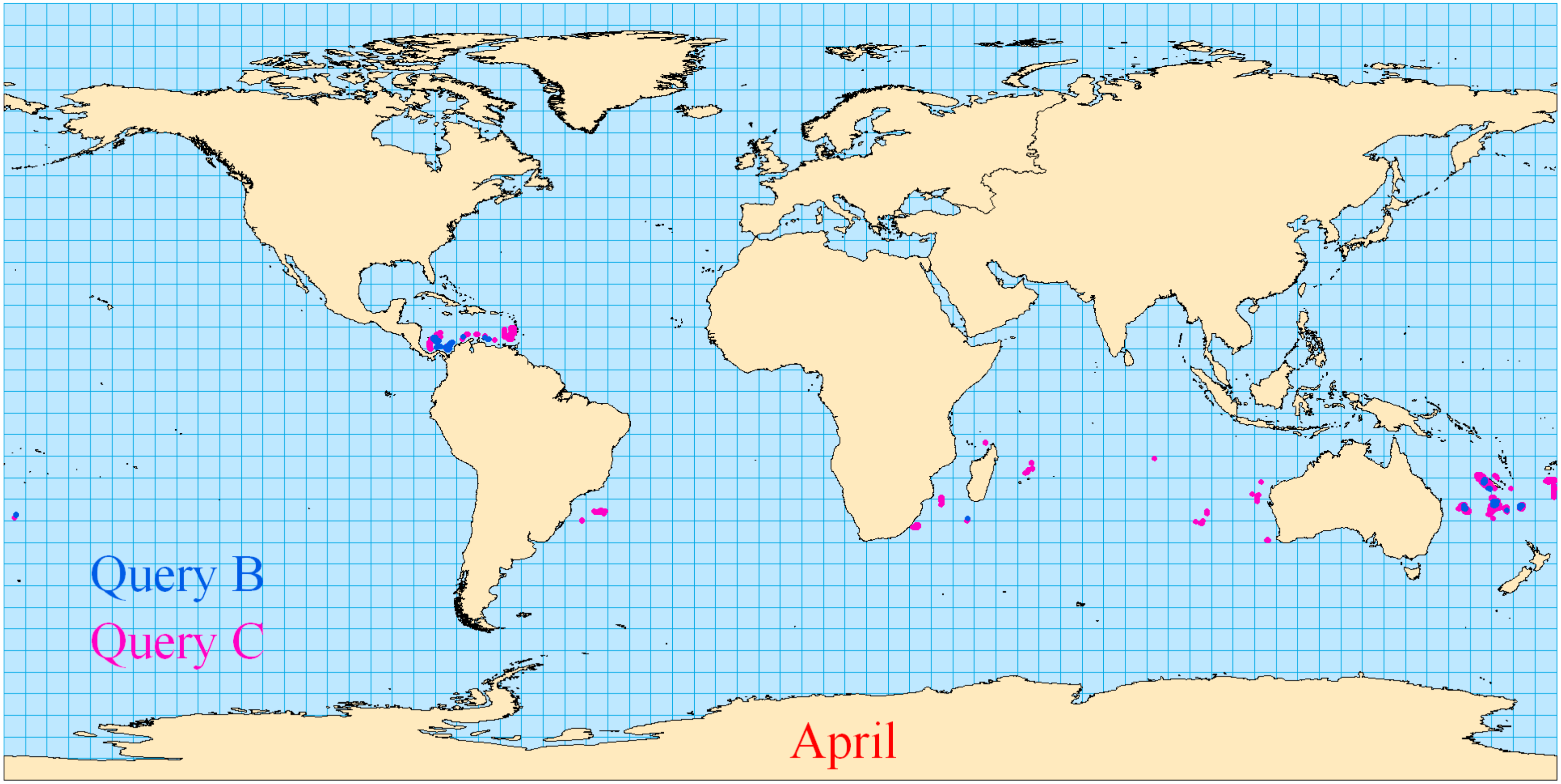

Figure 71. April analogous areas for Query B & C for Target Area in January.

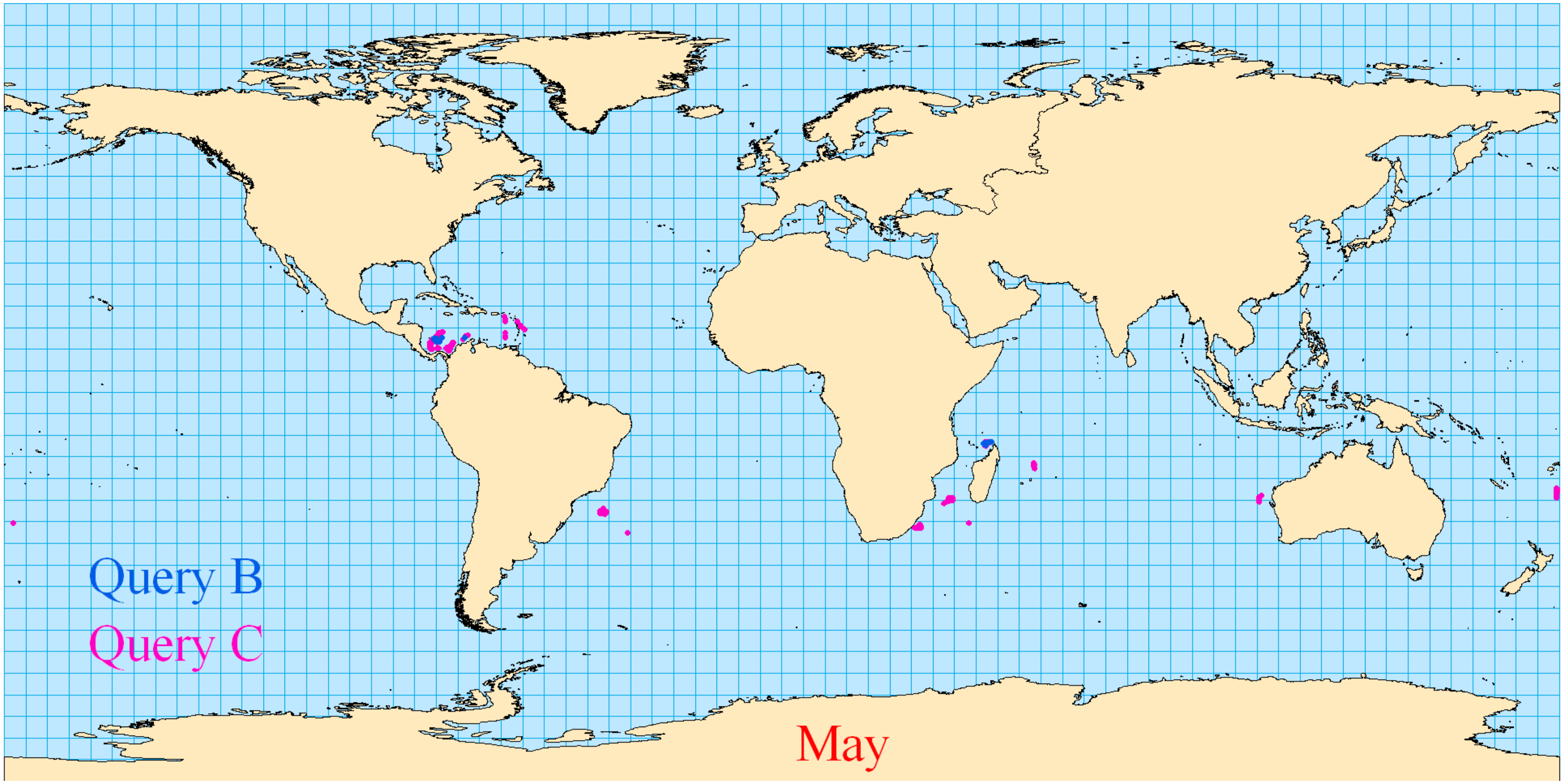

Figure 72. May analogous areas for Query B & C for Target Area in January.

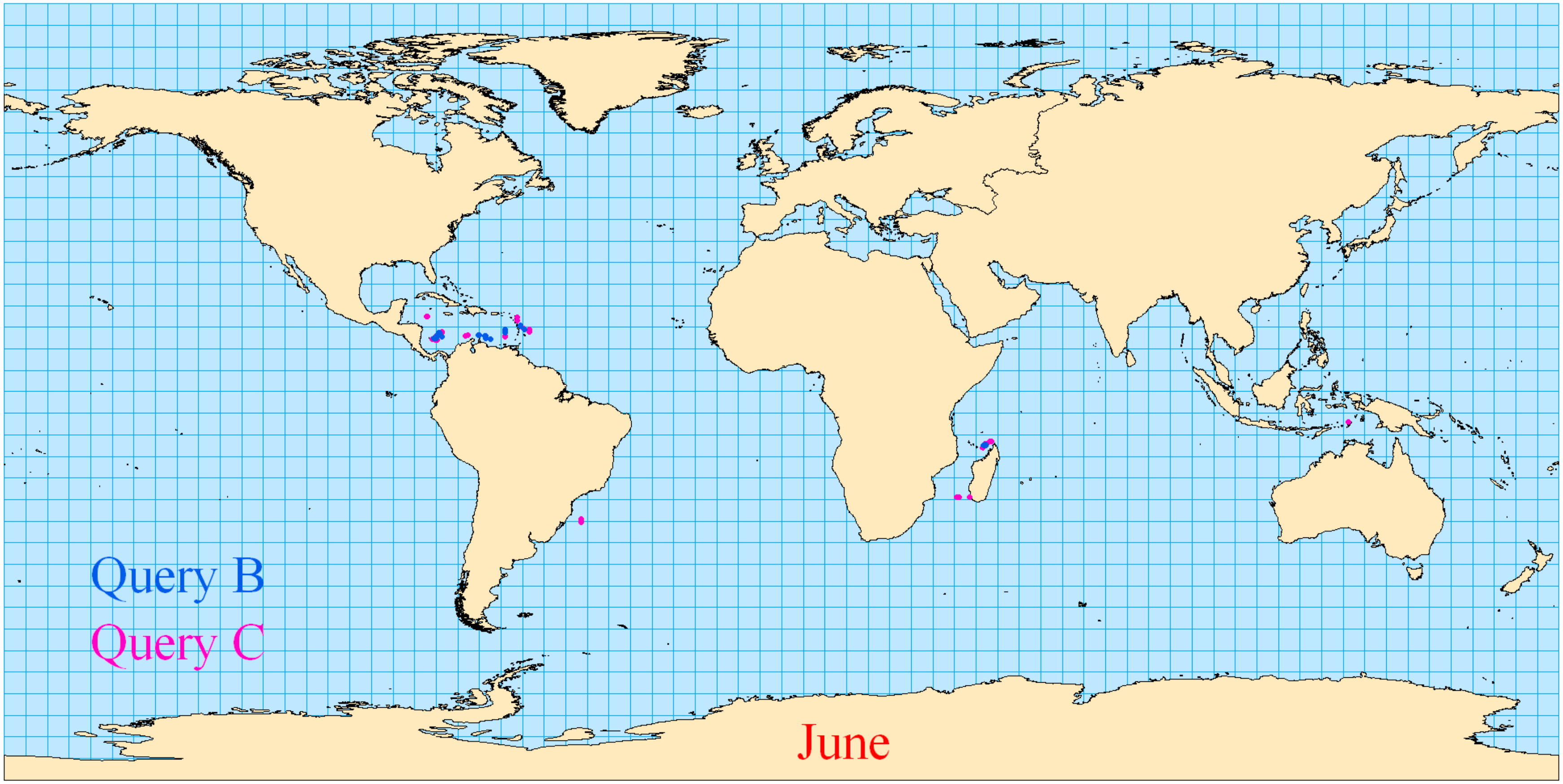

Figure 73. June analogous areas for Query B & C for Target Area in January.

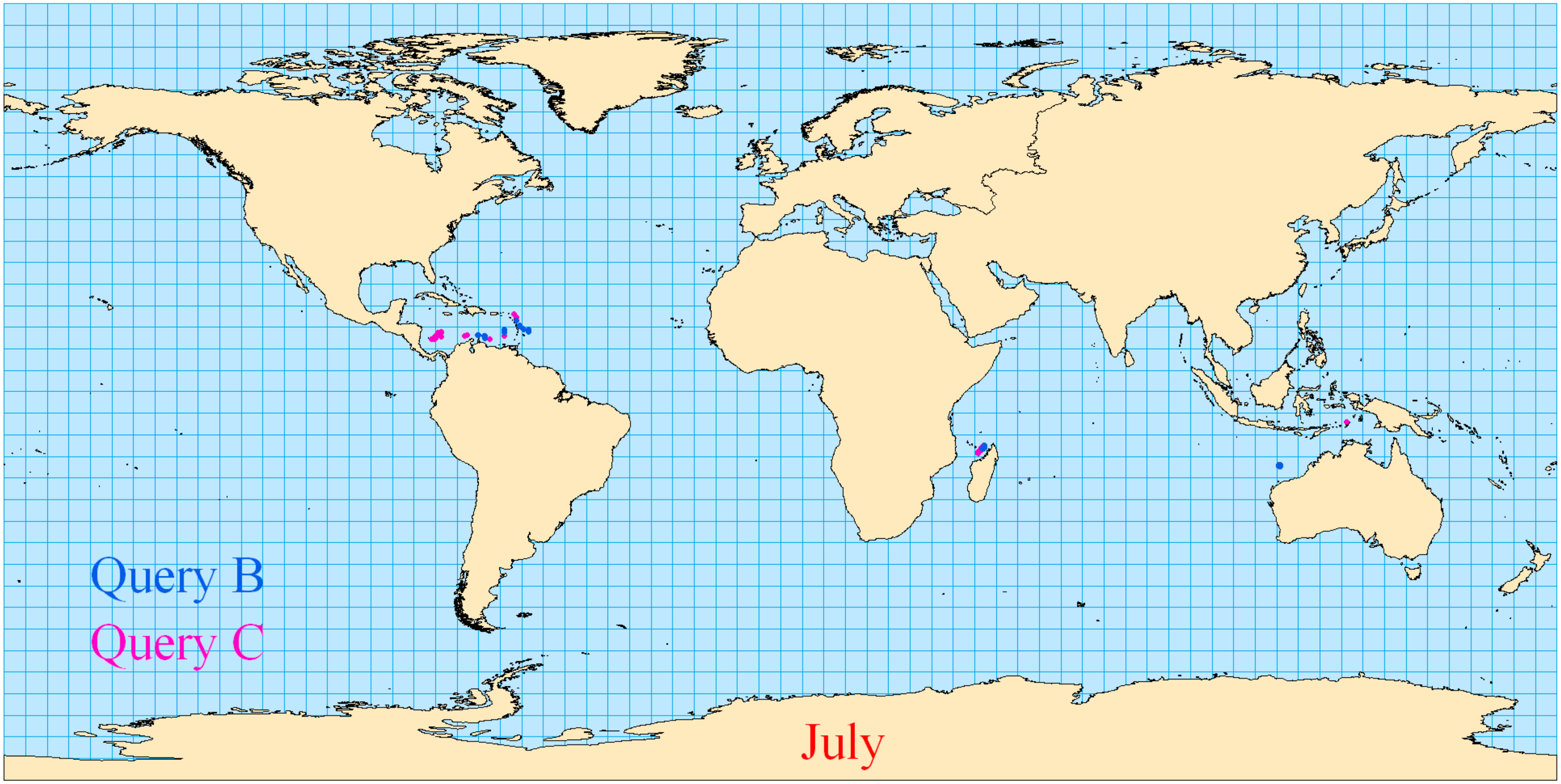

Figure 74. July analogous areas for Query B & C for Target Area in January.

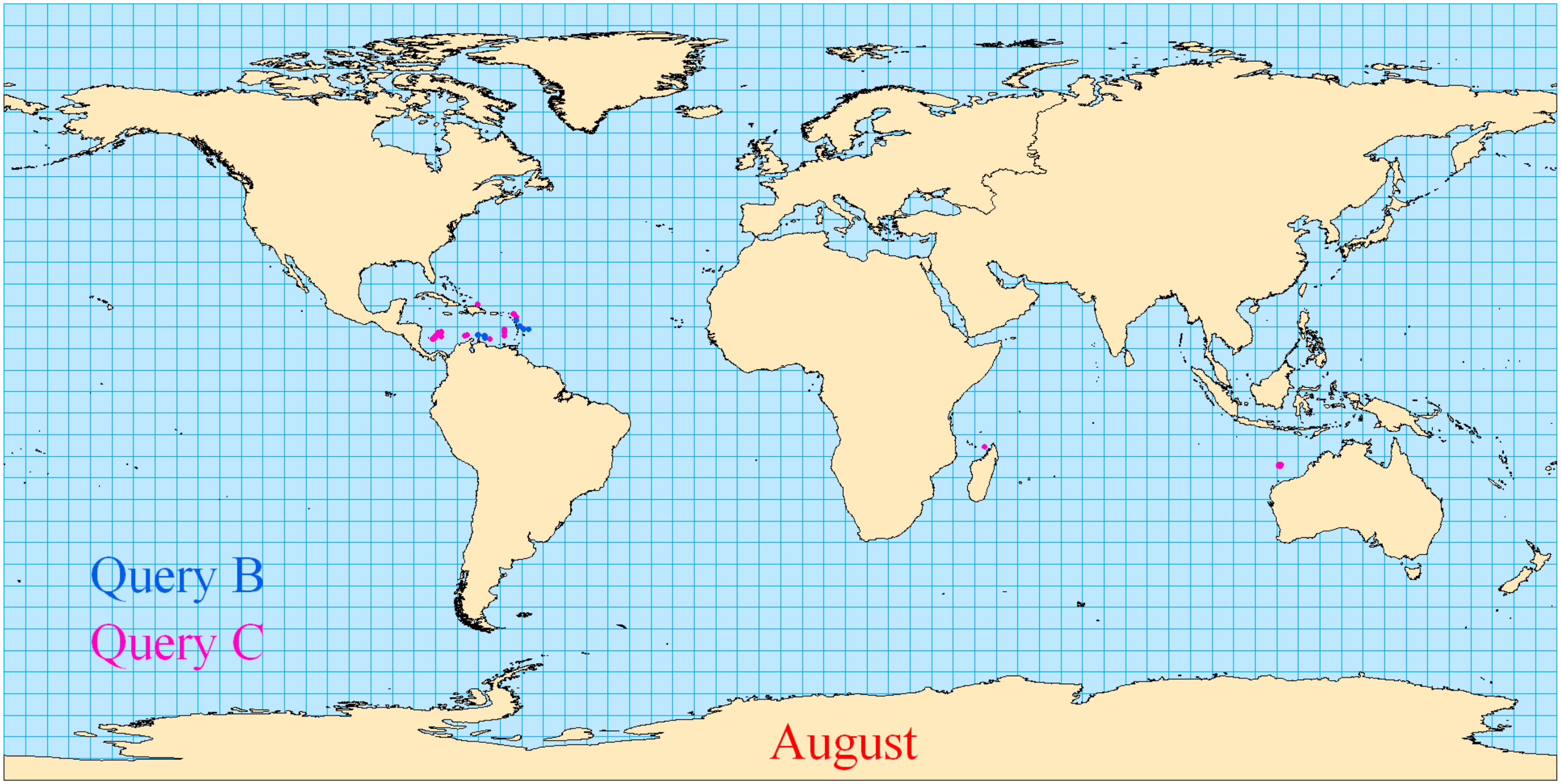

Figure 75. August analogous areas for Query B & C for Target Area in January.

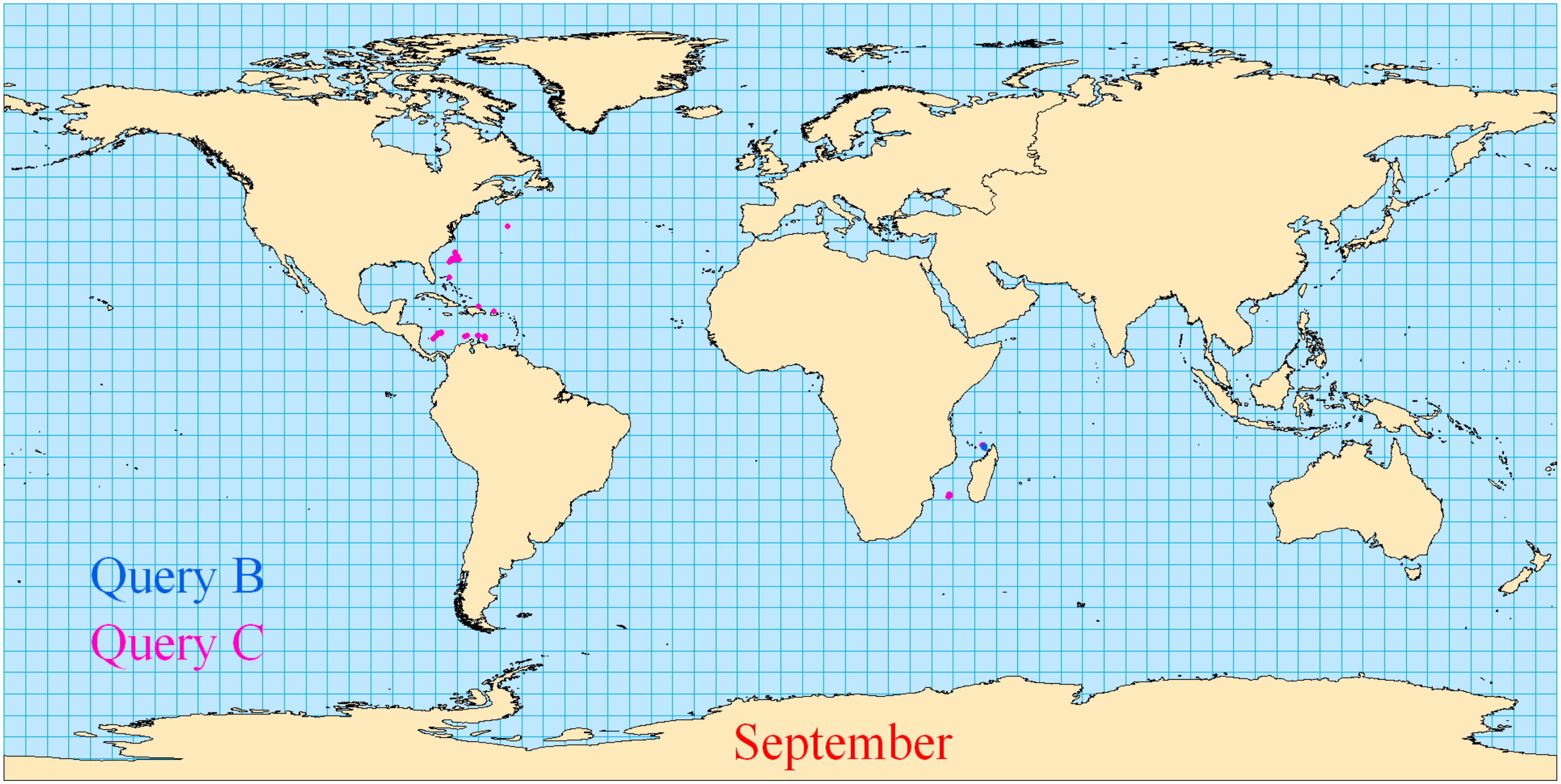

Figure 76. September analogous areas for Query B & C for Target Area in January.

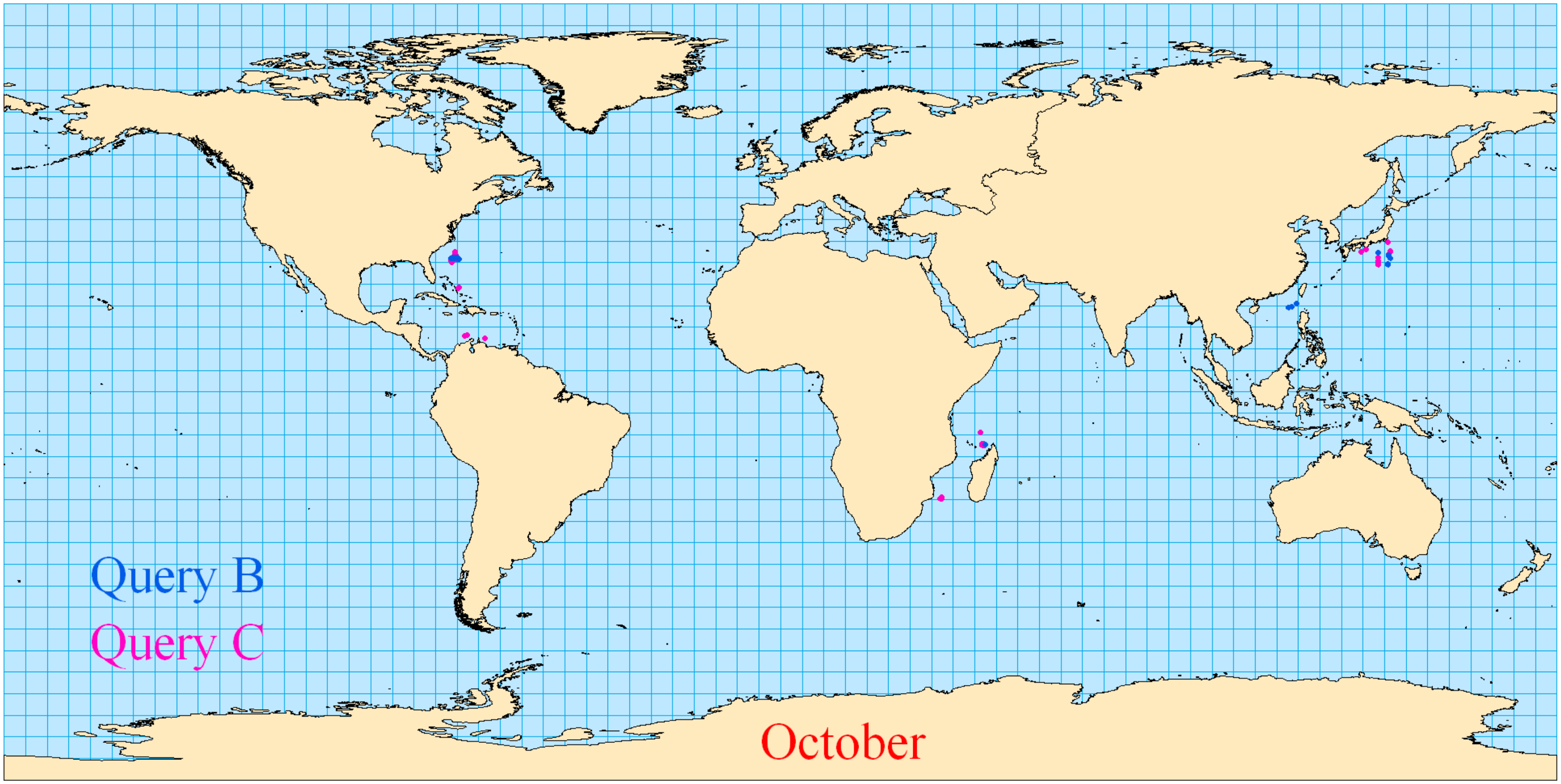

Figure 77. October analogous areas for Query B & C for Target Area in January.

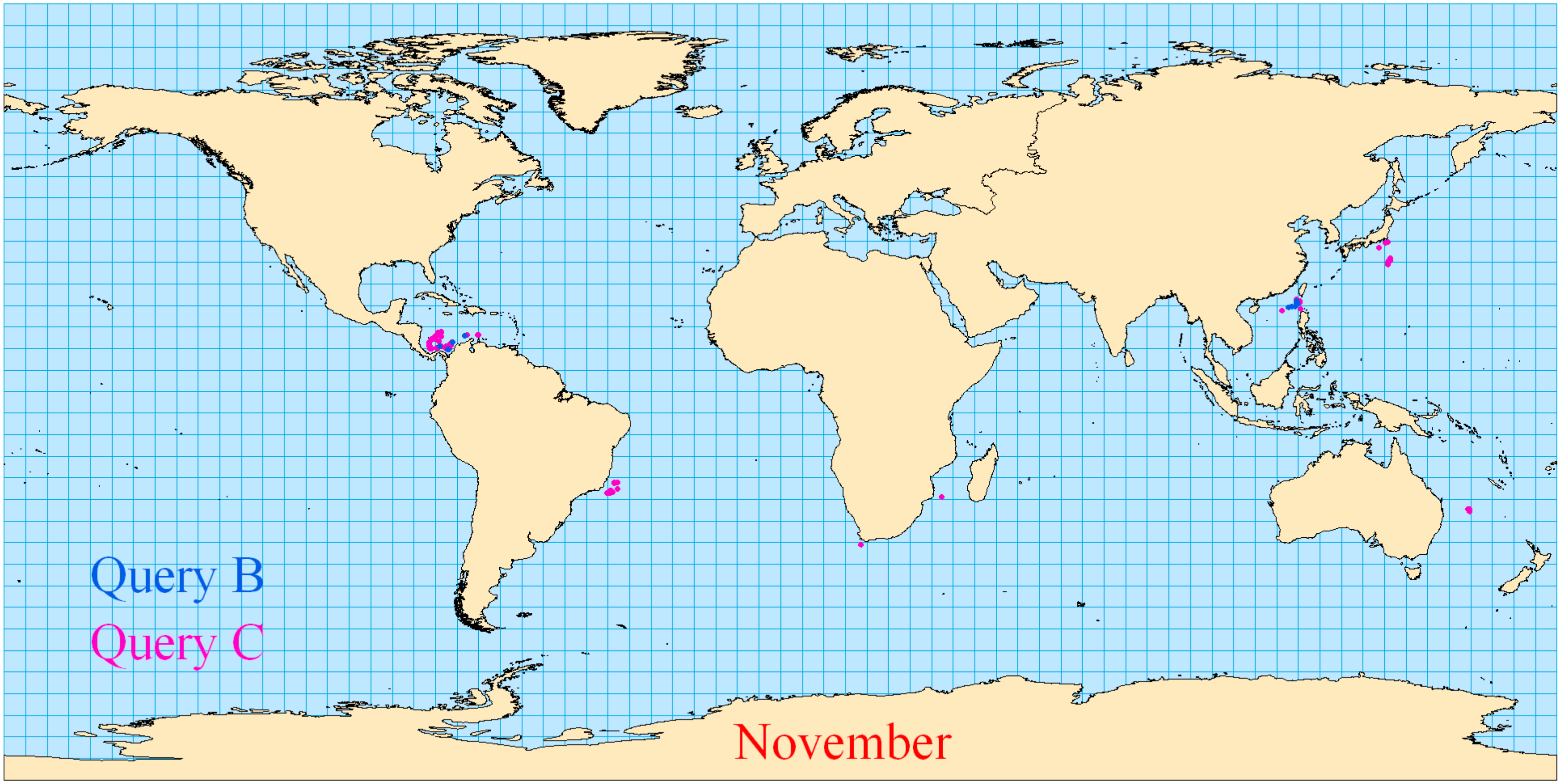

Figure 78. November analogous areas for Query B & C for Target Area in January.

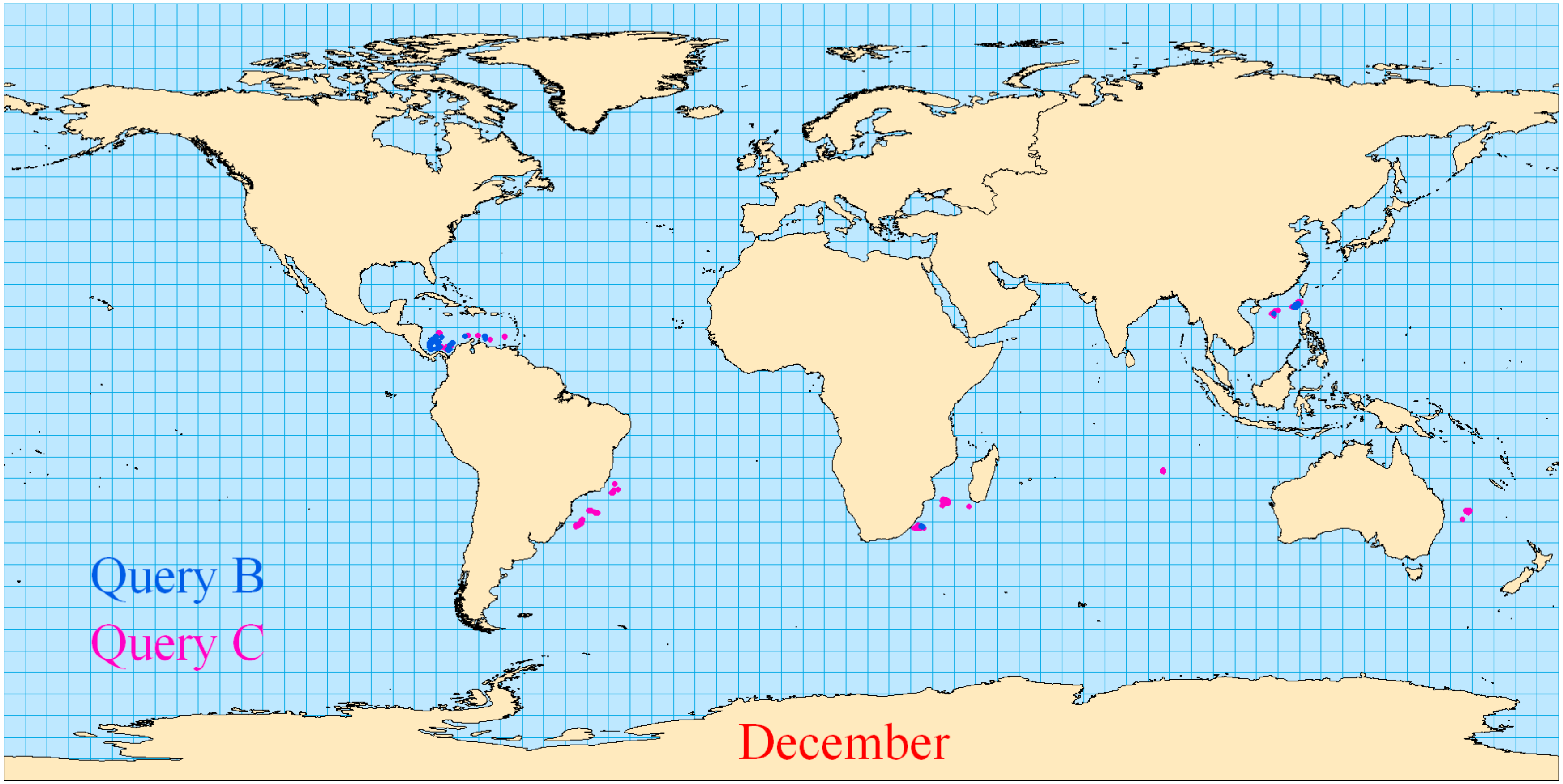

Figure 79. December analogous areas for Query B & C for Target Area in January.

Table 9 provides a summary of the number of analogous areas returned in each month for the three different queries. Query C produced more than three and a half times more analogous areas than Query B, which produced more than 54 times more areas than Query A.

	Query A	Query B	Query C
January	5	94	277
February	3	134	378
March	4	168	435
April	0	88	475
May	0	22	176
June	0	27	65
July	0	10	62
August	0	10	42
September	0	5	54
October	0	21	66
November	0	14	104
December	0	64	179
TOTAL	**12**	**657**	**2313**

Table 9. Summary of monthly analogous areas for Query A, B, & C.

The results of the example analogous area search using the three different query types produced vastly different numbers of analogous areas. Query B and Query C produced analogous areas in waters close to US homeports although the number of them was greater in Query C. A comparison of the SSPs and ray traces for all three queries for this particular scenario reveals that relaxing the search criteria from Query A to Query C sacrificed little in terms of the analogous areas' environmental acoustic characteristics, while providing more options for training locations. Other mission types and target locations will likely demonstrate more significant differences than those shown in this example.

VI. CONCLUSIONS AND RECOMMENDATIONS

To ensure the United States Navy remains the premier Navy of the world amidst the growing navies of other countries, it is necessary to take advantage of the new, innovative technologies to enhance training opportunities to ensure USN forces are properly prepared for any mission. Training in environments close to homeports which are environmentally comparable to areas in which real-world missions will occur allows USN surface ships, submarines, and aircraft to efficiently prepare for those missions. Previous approached to analogous area determination have had limited applicability for various reasons; however, they have provided the ground work for the development of this analogous area tool which is immediately useful to the Fleet for any mission type and for any time and location in the world.

The analogous area tool was developed based on an assessment of acoustically relevant parameters of the undersea environment; further, the tool allows the USN user to select those parameters which are most important to sound propagation and detection. Data representative of those factors (sound speed profiles, wind speeds and wave heights, and sediment thicknesses and types) were accessed via publicly available UNCLASSIFIED databases, manipulated in scientific programs and spreadsheets, and ingested into a capable software program, ArcMap, for weighting, querying, and displaying of analogous areas.

This method utilized climatological data at a finer resolution and a larger coverage area than the previous methods and permitted the identification of worldwide analogous areas for any target location. In the process, shapefiles (.shp) of sound speed profile descriptors and mean wind speed and wave height were created that any organization can easily use in analogous area searches. Previous methods relied on MATLAB code, which requires knowledge of the programming language and can be very time consuming when changing weights and target areas. This method utilized the widely-used ArcMap software and the data files created here to easily conduct analogous area searches. Additional data can be easily included in the process in the form of

ArcMap compatible shapefiles (.shp). Use of this method is not limited to USN organizations. Any organization whose work depends on oceanographic and atmospheric properties can benefit from the use of this tool (e.g. oil exploration, undersea fiber-optic network installation, atmospheric climate change studies, ecological studies).

An ASW scenario to locate and track an enemy submarine was used to test the analogous area tool. The steps outlined in this thesis were followed, and three queries, each differently weighting the important parameters, were run. The resulting analogous areas for each month were variable, yet centered on the query criteria, and were a basis for performing a sensitivity analysis of the returned locations. The tool was validated by comparing sound speed profiles and acoustic ray traces of the analogous areas and the target area. The results demonstrated the accuracy of the tool and provided insight into the importance of parameter selection and proper weighting. The validation confirmed that the analogous area tool developed here is an accurate and robust product that the USN and others organizations can immediately use.

Because this was a developmental project intended for USW applications, only the most acoustically significant datasets were chosen. However, there is no limit to the number and types of datasets that ArcMap is capable of handling and, therefore, inclusion of other data types is recommended to improve the accuracy, applicability, and usefulness of the tool. While the data used in this thesis were UNCLASSIFIED, the addition of CLASSIFIED data is most likely beneficial to analogous area determination and is certainly recommended. CLASSIFIED data sets typically contain higher resolution data and may be of more tactical use than UNCLASSIFIED data sets.

One of the most desirable aspects of this analogous area tool is that *any* user has the ability to establish *any* query criteria around *any* parameter for *any* application. In the example here, only three query criteria were used, each with different weighting of parameters. It is important to avoid relaxing the search criteria to yield results that are inaccurate and have no usability; sensitivity analysis is definitely recommended to prevent this. It is recommended that users of this tool perform multiple queries to achieve analogous area locations that are useful for their specific purpose. Degree of similarity between the target and analogous areas must be balanced with usefulness of analogous areas returned.

The data used in this thesis were from climatological databases and do not entirely represent the environment that may be encountered in a target area at a specific time due to temporal variability and microscopic processes. Numerous databases exist and it is recommended that future work in analogous areas identify the most suitable databases to incorporate into the analogous area tool and to perform a sensitivity analysis of those databases.

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